

Methods and apparatuses for magnetizing an object and for calibrating a sensor device

Field of the Invention

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The present invention relates to a method and an apparatus for magnetizing an object, to a method and an apparatus for calibrating a force and torque sensor device, to a use of an apparatus for magnetizing an object in particular technical fields, and to a use of an apparatus for calibrating a force and torque sensor device in particular technical fields.

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Description of the Related Art

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Magnetic transducer technology finds application in the measurement of torque and position. It has been especially developed for the non-contacting measurement of torque in a shaft or any other part being subject to torque or linear motion. A rotating or reciprocating element or an element which is subject to an axial load or to shear forces can be provided with a magnetized region, i.e. a magnetic encoded region, and when the shaft is rotated or reciprocated, such a magnetic encoded region generates a characteristic signal in a magnetic field detector (like a magnetic coil) enabling to determine torque, force or position of the shaft.

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For such kind of sensors which are disclosed, for instance, in WO 02/063262, it is important to have an accurately defined magnetically encoded region which can be manufactured and calibrated with low cost.

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Summary of the Invention

It is an object of the present invention to provide a sensor device having a magnetically encoded region, wherein the sensor device shall be manufacturable and  
5 operable with low cost.

This object may be achieved by providing a method and an apparatus for magnetizing an object, a method and an apparatus for calibrating a force and torque sensor device, a use of an apparatus for magnetizing an object in particular technical  
10 fields, and a use of an apparatus for calibrating a force and torque sensor device in particular technical fields according to the independent claims.

According to an exemplary embodiment of the invention, a method for magnetizing a first object and/or a second object is provided, the method comprising the steps of  
15 arranging a first object in such a manner that the first object encloses a second object, and applying a first electrical signal to the second object, wherein the first electrical signal is adapted such that at least a portion of the first object and/or of the second object is magnetized.

20 According to another exemplary embodiment of the invention, an apparatus is provided for magnetizing a first object and/or a second object. The apparatus comprises a first object, a second object, and an electrical signal source. The first object is arranged in such a manner that the first object encloses the second object. The electrical signal source is adapted to apply a first electrical signal to the second  
25 object, wherein the first electrical signal is adapted such that at least a portion of the first object and/or of the second object is magnetized.

Moreover, according to another exemplary embodiment of the invention, a method

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for calibrating a force and torque sensor device is provided, the method comprising the steps of providing a force and torque sensor device having a magnetically encoded region on an object and a magnetic field detector adapted to detect a signal resulting from a force or a torque applied to the object, applying a pre-known force  
5 to the object, detecting a signal resulting from the pre-known force applied to the object, and calibrating the force and torque sensor device based on a correlation between the pre-known force and the detected signal resulting from the pre-known force.

10 Beyond this, according to another exemplary embodiment of the invention, an apparatus for calibrating a force and torque sensor device is provided, the apparatus comprising a force and torque sensor device, a pre-known force generating element, and a calibrating unit. The force and torque sensor device has a magnetically encoded region on an object and a magnetic field detector adapted to detect a signal  
15 resulting from a force or a torque applied to the object. The pre-known force generating element is adapted to apply a pre-known force to the object, and the calibrating unit is adapted to calibrate the force and torque sensor device based on a correlation between a pre-known force and a detected signal resulting from the pre-known force.

20 According to another exemplary embodiment of the invention, an apparatus having the above-mentioned features is used for magnetizing one of the group consisting of a mining shaft, a concrete processing cylinder, a push-pull rod in a gearbox, and a shaft of an engine.

25 According to another exemplary embodiment of the invention, an apparatus having the above-mentioned features is used for calibrating a force and torque sensor device of the group consisting of a mining shaft, a concrete processing cylinder, a push-pull

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rod in a gearbox, and a shaft of an engine.

Within this specification, the expression “magnetizing” particularly has the meaning that microscopic or elementary magnets like magnetic moments, grains or domains  
5 which are present within a magnetizable material are treated such that at least a part of them becomes aligned along a particular direction, so that a random magnetic orientation is at least partially removed.

The method for magnetizing a first object and the apparatus for magnetizing a first  
10 object according to the exemplary embodiments mentioned above have the advantage that a first object can be magnetized by applying an electrical signal to a second object which is surrounded by the first object. For instance, a wire or a shaft or a rod as the second element can be surrounded by a hollow cylinder as the first object. Applying an appropriate electrical signal to the second object then allows to  
15 generate a magnetized region in the first object due to a physical effect which is similar like the physical effects occurring in the case of a transformer. In other words, a time-dependent electrical signal, like a current pulse, flowing through the second object generates a magnetic field which influences magnetizable material of the first object in such a manner that it becomes magnetized. The magnetization  
20 scheme of the invention allows a cheap and easy magnetization even of large hollow cylinders – as they occur particularly in the field of mining and drilling equipment. Thus, a magnetically encoded region can be formed in an already existing industrial steel hollow cylinder or tube. This allows that also already existing magnetizable objects, for instance a drilling shaft, may be provided with a magnetically encoded  
25 region so that a torque, a bending force and an axial load applied to such an object can be measured by a simple magnetic field detector like a coil arranged adjacent to the magnetized object.

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According to the described embodiment, particularly the outer first object is magnetized. However, in case that also the inner second object is made of a magnetizable material, the second object is magnetized simultaneously.

5 Another advantage related to the method and the apparatus for magnetizing a second object according to exemplary embodiments of the invention is the opportunity to connect the first object to the second object at a selected position, for instance at an end portion of the first object and at an end portion of the second object. According to such an architecture, the current flowing through the second object is injected also  
10 in the first object to form a counter magnetic field there, which stabilizes the current distribution in the objects. Thus, a high quality magnetically encoded region may be formed in the second object, yielding a sensor with more reproducible and reliable properties.

15 According to the described embodiment, particularly the inner second object is magnetized. However, in case that also the outer first object is made of a magnetizable material, the first object is magnetized simultaneously.

In the following, the method and the apparatus for calibrating a force and torque  
20 sensor device will be explained. One idea of this calibrating method is to simply apply a pre-known calibrating force, for instance a known mass or weight, to an object having a magnetically encoded region (which may be generated, for instance, according to the method of the invention of magnetizing an object). Such a weight or gravity force applied to a torque and force sensor results in a magnetic signal which  
25 can be detected by a magnetic field detector arranged in the vicinity of the magnetically encoded region. Therefore, the correlated data pair of the applied force and the resulting detection signal of the magnetic field detector can be stored. The magnetically encoded region can be encoded, for instance, according to the above

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described method of magnetizing an object, or to the technology mentioned in WO 02/063262, or according to the so-called PCME technology which will be described below in detail.

- 5     The thus measured correlation between an axial load and a detected signal of the magnetic field detector can then be used for a calibration of the sensor. When the object calibrated in this manner is practically used (for instance as a drilling shaft), a measured detection signal can be associated with an corresponding axial load force, using the calibration data pair estimated using the known mass. It is also possible, during calibration, to measure a plurality of calibration data pairs to refine the calibration.

- Further, the data pair of a known axial load and a corresponding detecting signal may also serve as an calibration information which may be used with a sensor which is subject of an applied torque during practical use. In other words, an axial load calibration calibrates a torque sensor. This aspect is particularly advantageous in an application in which a very heavy object is used, for example in the context of a drilling shaft in a mining application, when the torque applied to such a drilling shaft shall be measured. In this case, it is very easy just to place the drilling shaft, for example a tube, on a stable ground base and to put a known mass element on the upper end of the drilling shaft. In contrast to this, it would be very difficult to apply a calibration torque to such a drilling shaft for calibrating a torque sensor. It is easier to calibrate a torque sensor by using a calibrating axial force.

- 25     According to further aspects of the invention, the methods and apparatuses mentioned above may be implemented in the frame of a mining shaft, a concrete processing cylinder, a push-pull rod in a gearbox, or a shaft of an engine. In all of these applications, the magnetization and the calibration of such a torque, force and

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position sensor is highly advantageous, since it allows to manufacture a highly accurate and reliably calibrated force, position and torque sensor with low costs. Particularly, mining and drilling equipment may be provided with the systems of the invention, and may be used for monitoring a drilling direction and drilling forces.

- 5 Further applications of the invention are the recognition and the analysis of engine knocking.

Thus, a real-time measurement of actual mechanical forces applied and being effective "on the job" of large mining and drilling equipment is enabled according to  
10 the invention. The harsh outdoor conditions and dealing with abrasive materials is something traditional sensing technologies have difficulties to deal with, whereas the systems of the invention are compatible with such conditions without any problems. Mechanical forces which may be measured according to the invention are torque, bending, axial load and potential mining equipment overloads.

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By the magnetization method of the invention, a unique power-shaft encoding process is employed which allows utilizing the magnetic properties of many types of industrial steel so that a standard drilling shaft turns into a high precision force sensor. The actual time required to apply the encoding process is a fraction of a  
20 second and is permanent. After the desired section of the drilling shaft has been treated with the process of the invention, this part of the shaft is emanating a specific signal in relation to the applied mechanical forces to the shaft. This signal can be detected, for instance, by a passive electrical component that is placed several millimetres away from the shaft surface. Nothing needs to be attached to the shaft  
25 and nothing needs to touch the shaft, therefore the mean time between failure is very high (i.e. the invention provides a very reliable sensing solution). This non-contact mechanical force measurement principle relies only on the ferromagnetic properties of the drilling or power-transmitting shaft. It provides real-time information of any

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mechanical force that is travelling through the encoded section of the shaft, including rotational torque, bending forces, shearing forces and axial push-pull load. The overall signal bandwidth of the force-sensing technology is, according to an embodiment, 29kHz or around 100,000 measurement samples per second. In addition, a distinct signal will be emitted when the drilling shaft has been exposed to mechanical overload and is about to fail.

In large equipment it is often the case that the mechanical forces do not travel symmetrically or even distributed through the power or drilling shaft. Therefore, the magnetic field detector for instance “looks” at several critical locations at the shaft to get a larger picture. However, particularly in statically operating equipment (where the shaft does not rotate) it is often recommendable to work with one magnetic detecting device only.

The sensor of the invention can operate under water, in oil, or even in very dusty environment (like in concrete pumps or concrete mixing stations). The sensor can withstand temperatures in a very large range, particularly from  $-50^{\circ}\text{C}$  to  $+210^{\circ}\text{C}$ .

The sensor signal detection units may be connected to a custom specific electronic circuit that can be placed several metres away from the magnetic field detectors itself. Only two wires (“twisted pair”) may be implemented to connect a magnetic field detector with a corresponding electronic circuit. The output signal of such an electronic circuit can be a buffered analogue +5V signal, whereby +2500V may equal to zero torque. The overall electrical current consumption for a torque, axial load, or bending sensor is less than 5 mA per sensor channel.

The magnetic field detectors may be placed outside or inside a magnetically encoded hollow shaft. Assuming that mechanical forces transmitted through such a shaft are



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not passing through the magnetically encoded section symmetrically, several magnetic field detectors may be placed geometrically around the shaft to be able to capture a highly resolved “force picture”.

- 5     The encoding of large drilling shafts may be done “at site” to eliminate the potential need of shipping the heavy shaft to a specific factory location. The encoding equipment may be portable/mobile and can be used under almost all weather conditions. Under ideal circumstances, the drilling shaft can be placed on its own onto the ground for the encoding process. However, under the correct circumstances,
- 10    the drilling shaft can be encoded while still placed in the drilling or mining equipment. This is particularly possible if the shaft can be accessed and is not hidden away. Such a mobile magnetizing and calibration unit can be brought very close to a drilling shaft.
- 15    A feature of the sensing technology according to the invention is the way the permanent encoding drilling shaft may be calibrated. In case of a one meter diameter drilling shaft which is capable to deal with one million Nm torque, it will be normally be difficult to apply a “beam and weight” method for the shaft torque sensor calibration. When placing upright on a horizontal and structurally sound
- 20    surface, the measurement performances of the magnetically encoded shaft can be defined within a relative short time by relying on the way the “permanently” embedded signal source is behaving. This is particularly of interest when the drilling equipment has to be serviced and maintained at remote and difficult to reach
- 25    locations.

The mechanical force sensing technology according to the invention can be implemented in large-scale oil drilling equipment to detect the direction the drilling head is moving, and to measure the drilling pipes axial load (forward thrust) at the

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drilling heads location. In this application, the entire sensor system may be exposed to pressures of >1,500 bars and to temperatures >200°C. In another application, the sensing principle is measuring the mechanical forces applied to large-scale mobile/moving cranes. Here, the magnetically encoded sensor has the task to prevent the crane from falling (falling over or tilting) when critical load situations occur. Other applications of the invention are wind power plants, large extruder equipment, abrasive material pumping station, and large-scale industrial gear box systems.

It is mentioned that a second object (e.g. a shaft) enclosed by a first object (e.g. a hollow tube) can be magnetized by applying an electrical signal to the first object. This aspect is related to a method for magnetizing a second object, the method comprising the steps of arranging a first object in such a manner that the first object encloses the second object, and applying an electrical signal to the first object, wherein the electrical signal is adapted such that at least a portion of the second object is magnetized. The method works particularly fine when end portions of the second object outside the first object are short-circuited, for instance if two such end portions are connected with each other electrically by a wire guided outside of the first object.

Referring to the dependent claims, further exemplary embodiments of the invention will be described in the following.

In the following, exemplary embodiments of the method for magnetizing an object will be described. However, these embodiments also apply for the apparatus for magnetizing an object, for the method and the apparatus for calibrating a force and torque sensor device, for the use of an apparatus for magnetizing an object in particular technical fields, and for the use of an apparatus for calibrating a force and torque sensor device in particular technical fields.

The first electrical signal may be a first pulse signal or a sequence of subsequent pulse signals. Such a pulse signal can particularly be a signal which is different from zero only for a defined interval of time.

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For instance, in a time versus current diagram, the first pulse signal has a fast raising edge which is essentially vertical and has a slow falling edge. With such a pulse signal, the magnetically encoded region obtained has a high quality. It is also possible that a plurality of such pulses are subsequently applied to form a

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magnetically encoded region.

A second electrical signal may be applied to the second object after having applied the first electrical signal, wherein the second electrical signal may be adapted such that at least a portion of the first object and/or of the second object is magnetized, and wherein the second electrical signal differs from the first electrical signal concerning at least one of the group consisting of amplitude, sign, signal shape and duration.

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According to this embodiment, two pulses with opposite flowing direction of the electrical current may be applied to the second object.

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The second electrical signal may be a second pulse signal or a sequence of subsequent pulse signals, which, in a time versus current diagram may have a fast raising edge which is essentially vertical and may have a slow falling edge.

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According to an embodiment of the method of the invention, the first object may be magnetized by applying the first electrical signal and the second electrical signal such that in a direction essentially perpendicular to a surface of the first object and/or

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of the second object, a magnetic field structure is generated such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction, wherein the first direction is opposite to the second direction. This geometrical orientation of the two layers of magnetization results from two different pulses  
5 applied to the magnetizable material, so that a PCME-like sensor according to the below described technology may be manufactured.

The second electrical signal may also be an electrical current or an electrical voltage.

10 In the following, exemplary embodiments of the apparatus for magnetizing an object will be described. However, these embodiments also apply for the method for magnetizing an object, for the method and the apparatus for calibrating a force and torque sensor device, for the use of an apparatus for magnetizing an object in particular technical fields, and for the use of an apparatus for calibrating a force and  
15 torque sensor device in particular technical fields.

The first object may be a hollow tube. For instance, the first object enclosing the second object may be a hollow cylinder or the like. This structure provides a very symmetric geometry and is easy to manufacture. However, the first object being  
20 arranged as a hollow tube does not necessarily have to have a circular cross-section, but may also have a cross-section with the geometry of a polygon (e.g. a triangle or a square). Such a more asymmetric configuration may be used to refine sensing properties.

25 The second object may be a wire or a shaft or a hollow tube. Such a shaft or wire may be arranged along a symmetry axis of the first object, particularly of the first object embodied as a hollow tube. In an embodiment in which the second object is a hollow tube, the radius of the hollow tube as the second object is smaller than the

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radius of the hollow tube as the first object so that the second object can be surrounded by the first object. The second object being arranged as a hollow tube does not necessarily have to have a circular cross-section, but may also have a cross-section with the geometry of a polygon (e.g. a triangle or a square). Such a more  
5 asymmetric configuration may be used to refine sensing properties.

The second object may be arranged at a centre of the first object. In this configuration, a very symmetric current and magnetic field distribution is achieved.

10 The electrical signal source may comprise a capacitor bank. Such a capacitor bank comprises a plurality of capacitors which together may generate a pulse signal with a very high current amplitude and a small time duration, particularly for magnetizing large objects, as they may occur in the field of mining and drilling equipment. Such a capacitor bank may, for instance, have a capacity of 0.5 F. As an alternative to a  
15 capacitor bank, the electrical signal source/ electrical power source may comprise a conventional power supply unit or power pack.

The first object may have a first connection and may have a second connection, and the second object may have a first electrical connection and a second electrical  
20 connection. The second electrical connection of the first object may be coupled to the first electrical connection of the second object. According to this embodiment, the two objects are coupled in a manner that a portion, for instance an end portion, of the first object is coupled to a portion, for instance an end portion, of the second object. By this configuration, the current flowing through the second object is injected into  
25 the first object, so that a "feedback" of the magnetic field generating current is achieved. By this feedback, a counter magnetic field is generated in the first object which, together with the current flowing through the second object, provides a very symmetric configuration and yields an advantageous current distribution within the

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object. A torque and force sensor with a magnetic encoding of this kind, has a very high signal to noise ratio and only a small hysteresis behaviour.

Referring to the previously described embodiment, the electrical signal source may  
5 be connected such that a first electrical signal is applicable between the first electrical connection of the first object and the second electrical connection of the second object. According to this circuitry, the current is flowing from the first electrical connection of the first object to the second electrical connection of the first object, from there to the first electrical connection of the second object, and from there to  
10 the second electrical connection of the second object.

The first object may have a third electrical connection, and the second object may have a third electrical connection.

Referring to this embodiment, the electrical signal source may be connected such that  
15 a first electrical signal is applicable between the first electrical connection of the first object and the second electrical connection of the second object, and such that a second electrical signal is applicable between the third electrical connection of the first object and the third electrical connection of the second object. This  
20 configuration allows to apply magnetizing currents from both end portions of the first and second objects, whereas the first and second objects are coupled electrically at their centre portions with each other.

The apparatus may further comprise an electrically conductive coupling element  
25 arranged to couple the second electrical connection of the first object to the first electrical connection of the second object. Such a coupling element may be an electrically conductive plate, like a metal plate, which may be coupled with an end portion of a shaft as the second object and coupled with an end surface of a hollow

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tube as the first object. However, the electrically conductive coupling element may also be realized as a simple wire or the like. The electrically conductive coupling element may also be realized as an electrically conducting liquid, e.g. on the basis of mercury.

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The second object, in addition to the first object, may be adapted to be magnetized when the first electrical signal is applied. In other words, according to the described arrangement of the first object enclosing the second object, both of the objects can be magnetized and used as magnetized objects of a torque or force sensor.

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The second object may comprise a first connection and a second connection, wherein the electrical signal source may be connected between the first connection and the second connection of the second object. According to this circuitry, the electrical signal source may be disconnected from the first object. In other words, this configuration can be considered as a transformer-like arrangement, wherein the first object surrounding the second object can be magnetized without any direct ohmic contact between the two objects. In this context, the magnetization of the first object is generated by the electrical signal propagating through the second object and forcing elementary magnets of the material of the first object to become aligned.

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According to an exemplary embodiment, a portion of the second object may be free from an enclosure with the first object, and the apparatus may further comprise a shielding element which is arranged and adapted to electromagnetically shield the portion of the second object being free from an enclosure with the first object from the first object. This embodiment takes into account that a wiring of the second object back to the electrical signal source may also produce a magnetic field which influences the first object in a way that the magnetization generated by the part of the second object being enclosed or surrounded by the first object is weakened. In order

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to avoid such an undesired weakening and to achieve a homogeneous and reproducible magnetization of the first object, the shielding element shields the magnetic field generated by the part of the wiring of the second object which is not covered by the first object.

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Such a shielding element may be an element, for instance a tube, which may be optionally made of a magnetizable material which is arranged between the first object and the portion of the second object being from an enclosure with the first object. In this configuration, the shielding element forms some kind of magnetic “shadow” to magnetically decouple the first object from the part of the second object which is not covered by the second object.

Alternatively, the shielding element may be a tube (optionally made of a magnetizable material) which is arranged to enclose the portion of the second object being free from an enclosure with the first object. According to this embodiment, the shielding tube surrounds at least a part of the part of the second object which is not surrounded by the first element.

As a further alternative, the shielding element may comprise a plurality of tubes (optionally made of a magnetizable material) which are arranged surrounding at least a part of the portion of the second object being free from an enclosure with the first object. Such shielding tubes may be arranged symmetrically around the part of the first object to be shielded.

In the following, embodiments of the apparatus for calibrating a force and torque sensor device. However, these embodiments also apply for the method and apparatus for magnetizing an object, for the method for calibrating a force and torque sensor device, for the use of an apparatus for magnetizing an object in particular technical



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fields, and for the use of an apparatus for calibrating a force and torque sensor device in particular technical fields.

5 In the calibrating apparatus, the pre-known force generating element may be a pre-known weight. This pre-known weight, for instance 1000 kg, may be simply put on the top of a hollow cylinder-like force and torque sensor device to be calibrated and forms a constant and pre-known axial load applied to the sensor device, so that a highly accurate calibration is possible.

10 Alternatively, the pre-known force generating element may be adapted to apply a pre-known shear stress. Also by applying a shear stress, a pair of data values (force; resulting magnetic signal) can be obtained as a basis for a calibration.

15 Alternatively, the pre-known force generating element may be adapted to be a pre-known torque, particularly a pre-known reactive torque.

The above and other aspects, objects, features and advantages of the present invention will become apparent from the following description and the appended claim, taken in conjunction with the accompanying drawings in which like parts or  
20 elements are denoted by like reference numbers.

#### Brief Description of the Drawings

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The accompanying drawings, which are included to provide a further understanding of the invention and constitute a part of the specification illustrate embodiments of the invention.

Fig. 1 shows a torque sensor with a sensor element according to an exemplary embodiment of the present invention for explaining a method of manufacturing a torque sensor according to an exemplary embodiment of the present invention.

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Fig. 2a shows an exemplary embodiment of a sensor element of a torque sensor according to the present invention for further explaining a principle of the present invention and an aspect of an exemplary embodiment of a manufacturing method of the present invention.

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Fig. 2b shows a cross-sectional view along AA' of Fig. 2a.

Fig. 3a shows another exemplary embodiment of a sensor element of a torque sensor according to the present invention for further explaining a principle of the present invention and an exemplary embodiment of a method of manufacturing a torque sensor according to the present invention.

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Fig. 3b shows a cross-sectional representation along BB' of Fig. 3a.

Fig. 4 shows a cross-sectional representation of the sensor element of the torque sensor of Figs. 2a and 3a manufactured in accordance with a method according to an exemplary embodiment of the present invention.

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Fig. 5 shows another exemplary embodiment of a sensor element of a torque sensor according to the present invention for further explaining an exemplary embodiment of a manufacturing method of manufacturing a torque sensor according to the present invention.

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Fig. 6 shows another exemplary embodiment of a sensor element of a torque sensor according to the present invention for further explaining an exemplary embodiment of a manufacturing method for a torque sensor according to the present invention.

- 5 Fig. 7 shows a flow-chart for further explaining an exemplary embodiment of a method of manufacturing a torque sensor according to the present invention.

Fig. 8 shows a current versus time diagram for further explaining a method according to an exemplary embodiment of the present invention.

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Fig. 9 shows another exemplary embodiment of a sensor element of a torque sensor according to the present invention with an electrode system according to an exemplary embodiment of the present invention.

- 15 Fig. 10a shows another exemplary embodiment of a torque sensor according to the present invention with an electrode system according to an exemplary embodiment of the present invention.

- 20 Fig. 10b shows the sensor element of Fig. 10a after the application of current surges by means of the electrode system of Fig. 10a.

Fig. 11 shows another exemplary embodiment of a torque sensor element for a torque sensor according to the present invention.

- 25 Fig. 12 shows a schematic diagram of a sensor element of a torque sensor according to another exemplary embodiment of the present invention showing that two magnetic fields may be stored in the shaft and running in endless circles.

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Fig. 13 is another schematic diagram for illustrating PCME sensing technology using two counter cycle or magnetic field loops which may be generated in accordance with a manufacturing method according to the present invention.

- 5 Fig. 14 shows another schematic diagram for illustrating that when no mechanical stress is applied to the sensor element according to an exemplary embodiment of the present invention, magnetic flux lines are running in its original paths.

- 10 Fig. 15 is another schematic diagram for further explaining a principle of an exemplary embodiment of the present invention.

Fig. 16 is another schematic diagram for further explaining the principle of an exemplary embodiment of the present invention.

- 15 Figs. 17 – 22 are schematic representations for further explaining a principle of an exemplary embodiment of the present invention.

- Fig. 23 is another schematic diagram for explaining a principle of an exemplary embodiment of the present invention.

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Figs. 24, 25 and 26 are schematic diagrams for further explaining a principle of an exemplary embodiment of the present invention.

- 25 Fig. 27 is a current versus time diagram for illustrating a current pulse which may be applied to a sensor element according to a manufacturing method according to an exemplary embodiment of the present invention.

Fig. 28 shows an output signal versus current pulse length diagram according to an exemplary embodiment of the present invention.

5 Fig. 29 shows a current versus time diagram with current pulses according to an exemplary embodiment of the present invention which may be applied to sensor elements according to a method of the present invention.

10 Fig. 30 shows another current versus time diagram showing an exemplary embodiment of a current pulse applied to a sensor element such as a shaft according to a method of an exemplary embodiment of the present invention.

Fig. 31 shows a signal and signal efficiency versus current diagram in accordance with an exemplary embodiment of the present invention.

15 Fig. 32 is a cross-sectional view of a sensor element having a preferred PCME electrical current density according to an exemplary embodiment of the present invention.

20 Fig. 33 shows a cross-sectional view of a sensor element and an electrical pulse current density at different and increasing pulse current levels according to an exemplary embodiment of the present invention.

Figs. 34a and 34b show a spacing achieved with different current pulses of magnetic flows in sensor elements according to the present invention.

25 Fig. 35 shows a current versus time diagram of a current pulse as it may be applied to a sensor element according to an exemplary embodiment of the present invention.

Fig. 36 shows an electrical multi-point connection to a sensor element according to an exemplary embodiment of the present invention.

5 Fig. 37 shows a multi-channel electrical connection fixture with spring loaded contact points to apply a current pulse to the sensor element according to an exemplary embodiment of the present invention.

Fig. 38 shows an electrode system with an increased number of electrical connection points according to an exemplary embodiment of the present invention.

10 Fig. 39 shows an exemplary embodiment of the electrode system of Fig. 37.

Fig. 40 shows shaft processing holding clamps used for a method according to an exemplary embodiment of the present invention.

15 Fig. 41 shows a dual field encoding region of a sensor element according to the present invention.

20 Fig. 42 shows a process step of a sequential dual field encoding according to an exemplary embodiment of the present invention.

Fig. 43 shows another process step of the dual field encoding according to another exemplary embodiment of the present invention.

25 Fig. 44 shows another exemplary embodiment of a sensor element with an illustration of a current pulse application according to another exemplary embodiment of the present invention.

Fig. 45 shows schematic diagrams for describing magnetic flux directions in sensor elements according to the present invention when no stress is applied.

5 Fig. 46 shows magnetic flux directions of the sensor element of Fig. 45 when a force is applied.

Fig. 47 shows the magnetic flux inside the PCM encoded shaft of Fig. 45 when the applied torque direction is changing.

10 Fig. 48 shows a 6-channel synchronized pulse current driver system according to an exemplary embodiment of the present invention.

Fig. 49 shows a simplified representation of an electrode system according to another exemplary embodiment of the present invention.

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Fig. 50 is a representation of a sensor element according to an exemplary embodiment of the present invention.

20 Fig. 51 is another exemplary embodiment of a sensor element according to the present invention having a PCME process sensing region with two pinning field regions.

25 Fig. 52 is a schematic representation for explaining a manufacturing method according to an exemplary embodiment of the present invention for manufacturing a sensor element with an encoded region and pinning regions.

Fig. 53 is another schematic representation of a sensor element according to an exemplary embodiment of the present invention manufactured in accordance with a

manufacturing method according to an exemplary embodiment of the present invention.

Fig. 54 is a simplified schematic representation for further explaining an exemplary  
5 embodiment of the present invention.

Fig. 55 is another simplified schematic representation for further explaining an exemplary embodiment of the present invention.

10 Fig. 56 shows an application of a torque sensor according to an exemplary embodiment of the present invention in a gear box of a motor.

Fig. 57 shows a torque sensor according to an exemplary embodiment of the present invention.

15 Fig. 58 shows a schematic illustration of components of a non-contact torque sensing device according to an exemplary embodiment of the present invention.

Fig. 59 shows components of a sensing device according to an exemplary  
20 embodiment of the present invention.

Fig. 60 shows arrangements of coils with a sensor element according to an exemplary embodiment of the present invention.

25 Fig. 61 shows a single channel sensor electronics according to an exemplary embodiment of the present invention.



Fig. 62 shows a dual channel, short circuit protected system according to an exemplary embodiment of the present invention.

5 Fig. 63 shows a sensor according to another exemplary embodiment of the present invention.

Fig. 64 illustrates an exemplary embodiment of a secondary sensor unit assembly according to an exemplary embodiment of the present invention.

10 Fig. 65 illustrates two configurations of a geometrical arrangement of primary sensor and secondary sensor according to an exemplary embodiment of the present invention.

15 Fig. 66 is a schematic representation for explaining that a spacing between the secondary sensor unit and the sensor host is preferably as small as possible.

Fig. 67 is an embodiment showing a primary sensor encoding equipment.

20 **Fig. 68A** shows a magnetizing apparatus without involving an object enclosing another object.

**Fig. 68B** shows a magnetizing apparatus according to the invention involving an object enclosing another object.

25 **Fig. 68C** shows a schematic view of a torque and force sensing device with a magnetically encoded region formed according to the invention.

**Fig. 68D** shows a signal versus torque diagram of a torque and force sensing device magnetized with the magnetizing apparatus shown in Fig. 68A.

5 **Fig. 68E** shows a signal versus torque diagram of a torque and force sensing device magnetized with the magnetizing apparatus shown in Fig. 68B.

**Fig. 69** is a schematic view illustrating the principle of a method for magnetizing an object according to the invention.

10 **Figs. 70A and 70B** are schematic views illustrating an apparatus for magnetizing an object according to the invention.

**Fig. 70C** is a schematic view illustrating another apparatus for magnetizing an object according to the invention.

15 **Fig. 70D** is a diagram illustrating a pulse signal for magnetizing a object according to an apparatus as shown in Figs. 70A to 70C.

20 **Figs. 71A, 71B** illustrate another embodiment of an apparatus for magnetizing an object according to the invention.

**Fig. 72** illustrates still another apparatus for magnetizing an object according to an embodiment of the invention.

25 **Figs. 73A to 73D** show top views of different apparatuses for magnetizing an object according to embodiments of the invention.

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**Fig. 74** shows another apparatus for magnetizing an object according to the invention.

**Figs. 75A, 75B** show different views of an apparatus for calibrating a force and torque sensor device according to the invention.

**Figs. 76A, 76B** show schematic views of force and torque sensor devices according to the invention.

**Fig. 77** shows different views of magnetically encoded hollow cylinders.

**Fig. 78** shows views of a sensing device according to the invention.

**Fig. 79** illustrates still another apparatus for magnetizing an object.

**Fig. 80** illustrates still another apparatus for magnetizing an object according to an embodiment of the invention.

**Fig. 81** shows another apparatus for calibrating a force and torque sensor device according to the invention.

#### Detailed Description of Exemplary Embodiments of the Invention

It is disclosed a sensor having a sensor element such as a shaft wherein the sensor element may be manufactured in accordance with the following manufacturing steps

- applying a first current pulse to the sensor element;

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- wherein the first current pulse is applied such that there is a first current flow in a first direction along a longitudinal axis of the sensor element;
- wherein the first current pulse is such that the application of the current pulse generates a magnetically encoded region in the sensor element.

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It is disclosed that a further second current pulse may be applied to the sensor element. The second current pulse may be applied such that there is a second current flow in a direction along the longitudinal axis of the sensor element.

10 It is disclosed that the directions of the first and second current pulses may be opposite to each other. Also, each of the first and second current pulses may have a raising edge and a falling edge. For instance, the raising edge is steeper than the falling edge.

15 It is believed that the application of a current pulse may cause a magnetic field structure in the sensor element such that in a cross-sectional view of the sensor element, there is a first circular magnetic flow having a first direction and a second magnetic flow having a second direction. The radius of the first magnetic flow may be larger than the radius of the second magnetic flow. In shafts having a non-circular  
20 cross-section, the magnetic flow is not necessarily circular but may have a form essentially corresponding to and being adapted to the cross-section of the respective sensor element.

It is believed that if no torque is applied to a sensor element, there is no magnetic  
25 field or essentially no magnetic field detectable at the outside. When a torque or force is applied to the sensor element, there is a magnetic field emanated from the sensor element which can be detected by means of suitable coils. This will be described in further detail in the following.

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A torque sensor may have a circumferential surface surrounding a core region of the sensor element. The first current pulse is introduced into the sensor element at a first location at the circumferential surface such that there is a first current flow in the first direction in the core region of the sensor element. The first current pulse is discharged from the sensor element at a second location at the circumferential surface. The second location is at a distance in the first direction from the first location. The second current pulse may be introduced into the sensor element at the second location or adjacent to the second location at the circumferential surface such that there is the second current flow in the second direction in the core region or adjacent to the core region in the sensor element. The second current pulse may be discharged from the sensor element at the first location or adjacent to the first location at the circumferential surface.

As already indicated above, the sensor element may be a shaft. The core region of such shaft may extend inside the shaft along its longitudinal extension such that the core region surrounds a center of the shaft. The circumferential surface of the shaft is the outside surface of the shaft. The first and second locations are respective circumferential regions at the outside of the shaft. There may be a limited number of contact portions which constitute such regions. For instance, real contact regions may be provided, for example, by providing electrode regions made of brass rings as electrodes. Also, a core of a conductor may be looped around the shaft to provide for a good electric contact between a conductor such as a cable without isolation and the shaft.

The first current pulse and also the second current pulse may be not applied to the sensor element at an end face of the sensor element. The first current pulse may have a maximum between 40 and 1400 Ampere or between 60 and 800 Ampere or

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between 75 and 600 Ampere or between 80 and 500 Ampere. The current pulse may have a maximum such that an appropriate encoding is caused to the sensor element. However, due to different materials which may be used and different forms of the sensor element and different dimensions of the sensor element, a maximum of the  
5 current pulse may be adjusted in accordance with these parameters. The second pulse may have a similar maximum or may have a maximum approximately 10, 20, 30, 40 or 50 % smaller than the first maximum. However, the second pulse may also have a higher maximum such as 10, 20, 40, 50, 60 or 80 % higher than the first maximum.

10 A duration of those pulses may be the same. However, it is possible that the first pulse has a significant longer duration than the second pulse. However, it is also possible that the second pulse has a longer duration than the first pulse.

The first and/or second current pulses may have a first duration from the start of the  
15 pulse to the maximum and may have a second duration from the maximum to essentially the end of the pulse. The first duration may be significantly longer than the second duration. For example, the first duration may be smaller than 300 ms wherein the second duration may be larger than 300 ms. However, it is also possible that the first duration is smaller than 200 ms whereas the second duration is larger  
20 than 400 ms. Also, the first duration may be between 20 to 150 ms wherein the second duration may be between 180 to 700ms.

As already indicated above, it is possible to apply a plurality of first current pulses but also a plurality of second current pulses. The sensor element may be made of  
25 steel whereas the steel may comprise nickel. The sensor material used for the primary sensor or for the sensor element may be 50NiCr13 or X4CrNi13-4 or X5CrNiCuNb16-4 or X20CrNi17-4 or X46Cr13 or X20Cr13 or 14NiCr14 or S155 as

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set forth in DIN 1.2721 or 1.4313 or 1.4542 or 1.2787 or 1.4034 or 1.4021 or 1.5752 or 1.6928.

5 The first current pulse may be applied by means of an electrode system having at least a first electrode and a second electrode. The first electrode is located at the first location or adjacent to the first location and the second electrode is located at the second location or adjacent to the second location.

10 Each of the first and second electrodes may have a plurality of electrode pins. The plurality of electrode pins of each of the first and second electrodes may be arranged circumferentially around the sensor element such that the sensor element is contacted by the electrode pins of the first and second electrodes at a plurality of contact points at an outer circumferential surface of the shaft at the first and second locations.

15 As indicated above, instead of electrode pins laminar or two-dimensional electrode surfaces may be applied. For instance, electrode surfaces are adapted to surfaces of the shaft such that a good contact between the electrodes and the shaft material may be ensured.

20 At least one of the first current pulse and at least one of the second current pulse may be applied to the sensor element such that the sensor element has a magnetically encoded region such that in a direction essentially perpendicular to a surface of the sensor element, the magnetically encoded region of the sensor element has a magnetic field structure such that there is a first magnetic flow in a first direction and  
25 a second magnetic flow in a second direction. The first direction may be opposite to the second direction.

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In a cross-sectional view of the sensor element, there may be a first circular magnetic flow having the first direction and a first radius and a second circular magnetic flow having the second direction and a second radius. The first radius may be larger than the second radius.

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Furthermore, the sensor elements may have a first pinning zone adjacent to the first location and a second pinning zone adjacent to the second location.

The pinning zones may be manufactured in accordance with the following  
10 manufacturing method. According to this method, for forming the first pinning zone, at the first location or adjacent to the first location, a third current pulse is applied on the circumferential surface of the sensor element such that there is a third current flow in the second direction. The third current flow is discharged from the sensor element at a third location which is displaced from the first location in the second  
15 direction.

For forming the second pinning zone, at the second location or adjacent to the second location, a forth current pulse may be applied on the circumferential surface to the sensor element such that there is a forth current flow in the first direction. The forth  
20 current flow is discharged at a forth location which is displaced from the second location in the first direction.

A torque sensor may be provided comprising a first sensor element with a magnetically encoded region wherein the first sensor element has a surface. In a  
25 direction essentially perpendicular to the surface of the first sensor element, the magnetically encoded region of the first sensor element may have a magnetic field structure such that there is a first magnetic flow in a first direction and a second



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magnetic flow in a second direction. The first and second directions may be opposite to each other.

5 The torque sensor may further comprise a second sensor element with at least one magnetic field detector. The second sensor element may be adapted for detecting variations in the magnetically encoded region. More precisely, the second sensor element may be adapted for detecting variations in a magnetic field emitted from the magnetically encoded region of the first sensor element.

10 The magnetically encoded region may extend longitudinally along a section of the first sensor element, but does not extend from one end face of the first sensor element to the other end face of the first sensor element. In other words, the magnetically encoded region does not extend along all of the first sensor element but only along a section thereof.

15 The first sensor element may have variations in the material of the first sensor element caused by at least one current pulse or surge applied to the first sensor element for altering the magnetically encoded region or for generating the magnetically encoded region. Such variations in the material may be caused, for  
20 example, by differing contact resistances between electrode systems for applying the current pulses and the surface of the respective sensor element. Such variations may, for example, be burn marks or color variations or signs of an annealing.

The variations may be at an outer surface of the sensor element and not at the end  
25 faces of the first sensor element since the current pulses are applied to outer surface of the sensor element but not to the end faces thereof.

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A shaft for a magnetic sensor may be provided having, in a cross-section thereof, at least two circular magnetic loops running in opposite direction. Such shaft is believed to be manufactured in accordance with the above-described manufacturing method.

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Furthermore, a shaft may be provided having at least two circular magnetic loops which are arranged concentrically.

10

A shaft for a torque sensor may be provided which is manufactured in accordance with the following manufacturing steps where firstly a first current pulse is applied to the shaft. The first current pulse is applied to the shaft such that there is a first current flow in a first direction along a longitudinal axis of the shaft. The first current pulse is such that the application of the current pulse generates a magnetically encoded region in the shaft. This may be made by using an electrode system as described above and by applying current pulses as described above.

15

An electrode system may be provided for applying current surges to a sensor element for a torque sensor, the electrode system having at least a first electrode and a second electrode wherein the first electrode is adapted for location at a first location on an outer surface of the sensor element. A second electrode is adapted for location at a second location on the outer surface of the sensor element. The first and second electrodes are adapted for applying and discharging at least one current pulse at the first and second locations such that current flows within a core region of the sensor element are caused. The at least one current pulse is such that a magnetically encoded region is generated at a section of the sensor element.

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The electrode system may comprise at least two groups of electrodes, each comprising a plurality of electrode pins. The electrode pins of each electrode are

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arranged in a circle such that the sensor element is contacted by the electrode pins of the electrode at a plurality of contact points at an outer surface of the sensor element.

5 The outer surface of the sensor element does not include the end faces of the sensor element.

Fig. 1 shows an exemplary embodiment of a torque sensor according to the present invention. The torque sensor comprises a first sensor element or shaft 2 having a rectangular cross-section. The first sensor element 2 extends essentially along the  
10 direction indicated with X. In a middle portion of the first sensor element 2, there is the encoded region 4. The first location is indicated by reference numeral 10 and indicates one end of the encoded region and the second location is indicated by reference numeral 12 which indicates another end of the encoded region or the region to be magnetically encoded 4. Arrows 14 and 16 indicate the application of a current  
15 pulse. As indicated in Fig. 1, a first current pulse is applied to the first sensor element 2 at an outer region adjacent or close to the first location 10. For instance, as will be described in further detail later on, the current is introduced into the first sensor element 2 at a plurality of points or regions close to the first location and for instance surrounding the outer surface of the first sensor element 2 along the first location 10.  
20 As indicated with arrow 16, the current pulse is discharged from the first sensor element 2 close or adjacent or at the second location 12 for instance at a plurality or locations along the end of the region 4 to be encoded. As already indicated before, a plurality of current pulses may be applied in succession they may have alternating directions from location 10 to location 12 or from location 12 to location 10.

25

Reference numeral 6 indicates a second sensor element which is for instance a coil connected to a controller electronic 8. The controller electronic 8 may be adapted to further process a signal output by the second sensor element 6 such that an output

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signal may output from the control circuit corresponding to a torque applied to the first sensor element 2. The control circuit 8 may be an analog or digital circuit. The second sensor element 6 is adapted to detect a magnetic field emitted by the encoded region 4 of the first sensor element.

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It is believed that, as already indicated above, if there is no stress or force applied to the first sensor element 2, there is essentially no field detected by the second sensor element 6. However, in case a stress or a force is applied to the secondary sensor element 2, there is a variation in the magnetic field emitted by the encoded region such that an increase of a magnetic field from the presence of almost no field is detected by the second sensor element 6.

10

It has to be noted that according to other exemplary embodiments of the present invention, even if there is no stress applied to the first sensor element, it may be possible that there is a magnetic field detectable outside or adjacent to the encoded region 4 of the first sensor element 2. However, it is to be noted that a stress applied to the first sensor element 2 causes a variation of the magnetic field emitted by the encoded region 4.

15

In the following, with reference to Figs. 2a, 2b, 3a, 3b and 4, a method of manufacturing a torque sensor according to an exemplary embodiment of the present invention will be described. In particular, the method relates to the magnetization of the magnetically encoded region 4 of the first sensor element 2.

20

As may be taken from Fig. 2a, a current I is applied to an end region of a region 4 to be magnetically encoded. This end region as already indicated above is indicated with reference numeral 10 and may be a circumferential region on the outer surface of the first sensor element 2. The current I is discharged from the first sensor element

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2 at another end area of the magnetically encoded region (or of the region to be magnetically encoded) which is indicated by reference numeral 12 and also referred to a second location. The current is taken from the first sensor element at an outer surface thereof, for instance circumferentially in regions close or adjacent to location  
5 12. As indicated by the dashed line between locations 10 and 12, the current I introduced at or along location 10 into the first sensor element flows through a core region or parallel to a core region to location 12. In other words, the current I flows through the region 4 to be encoded in the first sensor element 2.

10 Fig. 2b shows a cross-sectional view along AA'. In the schematic representation of Fig. 2b, the current flow is indicated into the plane of the Fig. 2b as a cross. Here, the current flow is indicated in a center portion of the cross-section of the first sensor element 2. It is believed that this introduction of a current pulse having a form as described above or in the following and having a maximum as described above or in  
15 the following causes a magnetic flow structure 20 in the cross-sectional view with a magnetic flow direction into one direction here into the clockwise direction. The magnetic flow structure 20 depicted in Fig. 2b is depicted essentially circular. However, the magnetic flow structure 20 may be adapted to the actual cross-section of the first sensor element 2 and may be, for example, more elliptical.

20

Figs. 3a and 3b show a step of the method according to an exemplary embodiment of the present invention which may be applied after the step depicted in Figs. 2a and 2b. Fig. 3a shows a first sensor element according to an exemplary embodiment of the present invention with the application of a second current pulse and Fig. 3b shows a  
25 cross-sectional view along BB' of the first sensor element 2.

As may be taken from Fig. 3a, in comparison to Fig. 2a, in Fig. 3a, the current I indicated by arrow 16 is introduced into the sensor element 2 at or adjacent to

location 12 and is discharged or taken from the sensor element 2 at or adjacent to the location 10. In other words, the current is discharged in Fig. 3a at a location where it was introduced in Fig. 2a and vice versa. Thus, the introduction and discharging of the current I into the first sensor element 2 in Fig. 3a may cause a current through the  
5 region 4 to be magnetically encoded opposite to the respective current flow in Fig. 2a.

The current is indicated in Fig. 3b in a core region of the sensor element 2. As may be taken from a comparison of Figs. 2b and 3b, the magnetic flow structure 22 has a  
10 direction opposite to the current flow structure 20 in Fig. 2b.

As indicated before, the steps depicted in Figs. 2a, 2b and 3a and 3b may be applied individually or may be applied in succession of each other. When firstly, the step depicted in Figs. 2a and 2b is performed and then the step depicted in Figs. 3a and  
15 3b, a magnetic flow structure as depicted in the cross-sectional view through the encoded region 4 depicted in Fig. 4 may be caused. As may be taken from Fig. 4, the two current flow structures 20 and 22 are encoded into the encoded region together. Thus, in a direction essentially perpendicular to a surface of the first sensor element 2, in a direction to the core of the sensor element 2, there is a first magnetic flow  
20 having a first direction and then underlying there is a second magnetic flow having a second direction. As indicated in Fig. 4, the flow directions may be opposite to each other.

Thus, if there is no torque applied to the first torque sensor element 2, the two  
25 magnetic flow structures 20 and 22 may cancel each other such that there is essentially no magnetic field at the outside of the encoded region. However, in case a stress or force is applied to the first sensor element 2, the magnetic field structures 20 and 22 cease to cancel each other such that there is a magnetic field occurring at the

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outside of the encoded region which may then be detected by means of the secondary sensor element 6. This will be described in further detail in the following.

Fig. 5 shows another exemplary of a first sensor element 2 according to an  
5 exemplary embodiment of the present invention as may be used in a torque sensor  
according to an exemplary embodiment which is manufactured according to a  
manufacturing method according to an exemplary embodiment of the present  
invention. As may be taken from Fig. 5, the first sensor element 2 has an encoded  
region 4 which is for instance encoded in accordance with the steps and  
10 arrangements depicted in Figs. 2a, 2b, 3a, 3b and 4.

Adjacent to locations 10 and 12, there are provided pinning regions 42 and 44. These  
regions 42 and 44 are provided for avoiding a fraying of the encoded region 4. In  
other words, the pinning regions 42 and 44 may allow for a more definite beginning  
15 and end of the encoded region 4.

In short, the first pinning region 42 may be adapted by introducing a current 38 close  
or adjacent to the first location 10 into the first sensor element 2 in the same manner  
as described, for example, with reference to Fig. 2a. However, the current I is  
20 discharged from the first sensor element 2 at a first location 30 which is at a distance  
from the end of the encoded region close or at location 10. This further location is  
indicated by reference numeral 30. The introduction of this further current pulse I is  
indicated by arrow 38 and the discharging thereof is indicated by arrow 40. The  
current pulses may have the same form shaping maximum as described above.

25

For generating the second pinning region 44, a current is introduced into the first  
sensor element 2 at a location 32 which is at a distance from the end of the encoded  
region 4 close or adjacent to location 12. The current is then discharged from the first

- 40 -

sensor element 2 at or close to the location 12. The introduction of the current pulse I is indicated by arrows 34 and 36.

5 The pinning regions 42 and 44 may be such that the magnetic flow structures of these pinning regions 42 and 44 are opposite to the respective adjacent magnetic flow structures in the adjacent encoded region 4. As may be taken from Fig. 5, the pinning regions can be coded to the first sensor element 2 after the coding or the complete coding of the encoded region 4.

10 Fig. 6 shows another exemplary embodiment of the present invention where there is no encoding region 4. In other words, according to an exemplary embodiment of the present invention, the pinning regions may be coded into the first sensor element 2 before the actual coding of the magnetically encoded region 4.

15 Fig. 7 shows a simplified flow-chart of a method of manufacturing a first sensor element 2 for a torque sensor according to an exemplary embodiment of the present invention.

20 After the start in step S1, the method continues to step S2 where a first pulse is applied as described as reference to Figs. 2a and 2b. Then, after step S2, the method continues to step S3 where a second pulse is applied as described with reference to Figs. 3a and 3b.

25 Then, the method continues to step S4 where it is decided whether the pinning regions are to be coded to the first sensor element 2 or not. If it is decided in step S4 that there will be no pinning regions, the method continues directly to step S7 where it ends.



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If it is decided in step S4 that the pinning regions are to be coded to the first sensor element 2, the method continues to step S5 where a third pulse is applied to the pinning region 42 in the direction indicated by arrows 38 and 40 and to pinning region 44 indicated by the arrows 34 and 36. Then, the method continues to step S6  
5 where force pulses applied to the respective pinning regions 42 and 44. To the pinning region 42, a force pulse is applied having a direction opposite to the direction indicated by arrows 38 and 40. Also, to the pinning region 44, a force pulse is applied to the pinning region having a direction opposite to the arrows 34 and 36. Then, the method continues to step S7 where it ends.

10

In other words, two pulses may be applied for encoding of the magnetically encoded region 4. Those current pulses for instance have an opposite direction. Furthermore, two pulses respectively having respective directions are applied to the pinning region 42 and to the pinning region 44.

15

Fig. 8 shows a current versus time diagram of the pulses applied to the magnetically encoded region 4 and to the pinning regions. The positive direction of the y-axis of the diagram in Fig. 8 indicates a current flow into the x-direction and the negative direction of the y-axis of Fig. 8 indicates a current flow in the y-direction.

20

As may be taken from Fig. 8 for coding the magnetically encoded region 4, firstly a current pulse is applied having a direction into the x-direction. As may be taken from Fig. 8, the raising edge of the pulse is very sharp whereas the falling edge has a relatively long direction in comparison to the direction of the raising edge. As

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depicted in Fig. 8, the pulse may have a maximum of approximately 75 Ampere. In other applications, the pulse may be not as sharp as depicted in Fig. 8. However, the raising edge should be steeper or should have a shorter duration than the falling edge.

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Then, a second pulse is applied to the encoded region 4 having an opposite direction. The pulse may have the same form as the first pulse. However, a maximum of the second pulse may also differ from the maximum of the first pulse. Although the immediate shape of the pulse may be different.

5

Then, for coding the pinning regions, pulses similar to the first and second pulse may be applied to the pinning regions as described with reference to Figs. 5 and 6. Such pulses may be applied to the pinning regions simultaneously but also successfully for each pinning region. As depicted in Fig. 8, the pulses may have essentially the same

10 form as the first and second pulses. However, a maximum may be smaller.

Fig. 9 shows another exemplary embodiment of a first sensor element of a torque sensor according to an exemplary embodiment of the present invention showing an electrode arrangement for applying the current pulses for coding the magnetically

15 encoded region 4. As may be taken from Fig. 9, a conductor without an isolation may be looped around the first sensor element 2 which is may be taken from Fig. 9 may be a circular shaft having a circular cross-section. For ensuring a close fit of the conductor on the outer surface of the first sensor element 2, the conductor may be clamped as shown by arrows 64.

20

Fig. 10a shows another exemplary embodiment of a first sensor element according to an exemplary embodiment of the present invention. Furthermore, Fig. 10a shows another exemplary embodiment of an electrode system according to an exemplary embodiment of the present invention. The electrode system 80 and 82 depicted in

25 Fig. 10a contacts the first sensor element 2 which has a triangular cross-section with two contact points at each phase of the triangular first sensor element at each side of the region 4 which is to be encoded as magnetically encoded region. Overall, there

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are six contact points at each side of the region 4. The individual contact points may be connected to each other and then connected to one individual contact points.

5 If there is only a limited number of contact points between the electrode system and the first sensor element 2 and if the current pulses applied are very high, differing contact resistances between the contacts of the electrode systems and the material of the first sensor element 2 may cause burn marks at the first sensor element 2 at contact point to the electrode systems. These burn marks 90 may be color changes, may be welding spots, may be annealed areas or may simply be burn marks.

10 According to an exemplary embodiment of the present invention, the number of contact points is increased or even a contact surface is provided such that such burn marks 90 may be avoided.

15 Fig. 11 shows another exemplary embodiment of a first sensor element 2 which is a shaft having a circular cross-section according to an exemplary embodiment of the present invention. As may be taken from Fig. 11, the magnetically encoded region is at an end region of the first sensor element 2. According to an exemplary embodiment of the present invention, the magnetically encoded region 4 is not extend over the full length of the first sensor element 2. As may be taken from Fig.

20 11, it may be located at one end thereof. However, it has to be noted that according to an exemplary embodiment of the present invention, the current pulses are applied from an outer circumferential surface of the first sensor element 2 and not from the end face 100 of the first sensor element 2.

25 In the following, the so-called PCME ("Pulse-Current-Modulated Encoding") Sensing Technology will be described in detail, which can, according to an exemplary embodiment of the invention, be implemented to magnetize a magnetizable object which is then partially demagnetized according to the invention.

In the following, the PCME technology will partly described in the context of torque sensing. However, this concept may implemented in the context of position sensing as well.

- 5 In this description, there are a number of acronyms used as otherwise some explanations and descriptions may be difficult to read. While the acronyms “ASIC”, “IC”, and “PCB” are already market standard definitions, there are many terms that are particularly related to the magnetostriction based NCT sensing technology. It should be noted that in this description, when there is a reference to NCT technology  
10 or to PCME, it is referred to exemplary embodiments of the present invention.

**Table 1** shows a list of abbreviations used in the following description of the PCME technology.

15	<b>Acronym</b>	<b>Description</b>	<b>Category</b>
	ASIC	Application Specific IC	Electronics
	DF	Dual Field	Primary Sensor
	EMF	Earth Magnetic Field	Test Criteria
	FS	Full Scale	Test Criteria
20	Hot-Spotting	Sensitivity to nearby Ferro magnetic material	Specification
	IC	Integrated Circuit	Electronics
	MFS	Magnetic Field Sensor	Sensor
	Component		
	NCT	Non Contact Torque	Technology
25	PCB	Printed Circuit Board	Electronics
	PCME	Pulse Current Modulated Encoding	Technology
	POC	Proof-of-Concept	
	RSU	Rotational Signal Uniformity	Specification

	SCSP	Signal Conditioning & Signal Processing	Electronics
	SF	Single Field	Primary Sensor
	SH	Sensor Host	Primary Sensor
	SPHC	Shaft Processing Holding Clamp	Processing Tool
5	SSU	Secondary Sensor Unit	Sensor Component

**Table 1:** List of abbreviations

10 The magnetic principle based mechanical-stress sensing technology allows to design and to produce a wide range of “physical-parameter-sensors” (like Force Sensing, Torque Sensing, and Material Diagnostic Analysis) that can be applied where Ferro-Magnetic materials are used. The most common technologies used to build “magnetic-principle-based” sensors are: Inductive differential displacement  
 15 measurement (requires torsion shaft), measuring the changes of the materials permeability, and measuring the magnetostriction effects.

Over the last 20 years a number of different companies have developed their own and very specific solution in how to design and how to produce a magnetic principle  
 20 based torque sensor (i.e. ABB, FAST, Fraunhofer Institute, FT, Kubota, MDI, NCTE, RM, Siemens, and others). These technologies are at various development stages and differ in “how-it-works”, the achievable performance, the systems reliability, and the manufacturing / system cost.

25 Some of these technologies require that mechanical changes are made to the shaft where torque should be measured (chevrons), or rely on the mechanical torsion effect (require a long shaft that twists under torque), or that something will be attached to the shaft itself (press-fitting a ring of certain properties to the shaft surface,), or

coating of the shaft surface with a special substance. No-one has yet mastered a high-volume manufacturing process that can be applied to (almost) any shaft size, achieving tight performance tolerances, and is not based on already existing technology patents.

5

In the following, a magnetostriction principle based Non-Contact-Torque (NCT) Sensing Technology is described that offers to the user a whole host of new features and improved performances, previously not available. This technology enables the realization of a fully-integrated (small in space), real-time (high signal bandwidth) torque measurement, which is reliable and can be produced at an affordable cost, at any desired quantities. This technology is called: PCME (for Pulse-Current-Modulated Encoding) or Magnetostriction Transversal Torque Sensor.

10

The PCME technology can be applied to the shaft without making any mechanical changes to the shaft, or without attaching anything to the shaft. Most important, the PCME technology can be applied to any shaft diameter (most other technologies have here a limitation) and does not need to rotate / spin the shaft during the encoding process (very simple and low-cost manufacturing process) which makes this technology very applicable for high-volume application.

15

20 In the following, a Magnetic Field Structure (Sensor Principle) will be described.

The sensor life-time depends on a “closed-loop” magnetic field design. The PCME technology is based on two magnetic field structures, stored above each other, and running in opposite directions. When no torque stress or motion stress is applied to the shaft (also called Sensor Host, or SH) then the SH will act magnetically neutral (no magnetic field can be sensed at the outside of the SH).

25

**Fig.12** shows that two magnetic fields are stored in the shaft and running in endless circles. The outer field runs in one direction, while the inner field runs in the opposite direction.

- 5     **Fig.13** illustrates that the PCME sensing technology uses two Counter-Circular magnetic field loops that are stored on top of each other (Picky-Back mode).

When mechanical stress (like reciprocation motion or torque) is applied at both ends of the PCME magnetized SH (Sensor Host, or Shaft) then the magnetic flux lines of  
10    both magnetic structures (or loops) will tilt in proportion to the applied torque.

As illustrated in **Fig.14**, when no mechanical stresses are applied to the SH the magnetic flux lines are running in its original path. When mechanical stresses are applied the magnetic flux lines tilt in proportion to the applied stress (like linear  
15    motion or torque).

Depending on the applied torque direction (clockwise or anti-clockwise, in relation to the SH) the magnetic flux lines will either tilt to the right or tilt to the left. Where the magnetic flux lines reach the boundary of the magnetically encoded region, the  
20    magnetic flux lines from the upper layer will join-up with the magnetic flux lines from the lower layer and visa-versa. This will then form a perfectly controlled toroidal shape.

The benefits of such a magnetic structure are:

- 25     ☐ Reduced (almost eliminated) parasitic magnetic field structures when mechanical stress is applied to the SH (this will result in better RSU performances).

- 5      ☐ Higher Sensor-Output Signal-Slope as there are two “active” layers that compliment each other when generating a mechanical stress related signal. Explanation: When using a single-layer sensor design, the “tilted” magnetic flux lines that exit at the encoding region boundary have to create a “return passage” from one boundary side to the other. This effort effects how much signal is available to be sensed and measured outside of the SH with the secondary sensor unit.
- 10     ☐ There are almost no limitations on the SH (shaft) dimensions where the PCME technology will be applied to. The dual layered magnetic field structure can be adapted to any solid or hollow shaft dimensions.
- 15     ☐ The physical dimensions and sensor performances are in a very wide range programmable and therefore can be tailored to the targeted application.
- ☐ This sensor design allows to measure mechanical stresses coming from all three dimensions axis, including in-line forces applied to the shaft (applicable as a load-cell). Explanation: Earlier magnetostriction sensor designs (for example from FAST Technology) have been limited to be sensitive in 2 dimensional axis only, and could not measure in-line forces.

20     Referring to **Fig.15**, when torque is applied to the SH, the magnetic flux lines from both Counter-Circular magnetic loops are connecting to each other at the sensor region boundaries.

25     When mechanical torque stress is applied to the SH then the magnetic field will no longer run around in circles but tilt slightly in proportion to the applied torque stress. This will cause the magnetic field lines from one layer to connect to the magnetic field lines in the other layer, and with this form a toroidal shape.



Referring to **Fig.16**, an exaggerated presentation is shown of how the magnetic flux line will form an angled toroidal structure when high levels of torque are applied to the SH.

- 5 In the following, features and benefits of the PCM-Encoding (PCME) Process will be described.

The magnetostriction NCT sensing technology from NCTE according to the present invention offers high performance sensing features like:

10

- ☐ No mechanical changes required on the Sensor Host (already existing shafts can be used as they are)
- ☐ Nothing has to be attached to the Sensor Host (therefore nothing can fall off or change over the shaft-lifetime = high MTBF)
- 15 ☐ During measurement the SH can rotate, reciprocate or move at any desired speed (no limitations on rpm)
- ☐ Very good RSU (Rotational Signal Uniformity) performances
- ☐ Excellent measurement linearity (up to 0.01% of FS)
- ☐ High measurement repeatability
- 20 ☐ Very high signal resolution (better than 14 bit)
- ☐ Very high signal bandwidth (better than 10 kHz)

Depending on the chosen type of magnetostriction sensing technology, and the chosen physical sensor design, the mechanical power transmitting shaft (also called

25 “Sensor Host” or in short “SH”) can be used “as is” without making any mechanical changes to it or without attaching anything to the shaft. This is then called a “true” Non-Contact-Torque measurement principle allowing the shaft to rotate freely at any desired speed in both directions.

The here described PCM-Encoding (PCME) manufacturing process according to an exemplary embodiment of the present invention provides additional features no other magnetostriction technology can offer (Uniqueness of this technology):

5

- ☐ More then three times signal strength in comparison to alternative magnetostriction encoding processes (like the “RS” process from FAST).
- ☐ Easy and simple shaft loading process (high manufacturing through-putt).
- ☐ No moving components during magnetic encoding process (low complexity manufacturing equipment = high MTBF, and lower cost).
- 10 ☐ Process allows NCT sensor to be “fine-tuning” to achieve target accuracy of a fraction of one percent.
- ☐ Manufacturing process allows shaft “pre-processing” and “post-processing” in the same process cycle (high manufacturing through-putt).
- 15 ☐ Sensing technology and manufacturing process is ratio-metric and therefore is applicable to all shaft or tube diameters.
- ☐ The PCM-Encoding process can be applied while the SH is already assembled (depending on accessibility) (maintenance friendly).
- ☐ Final sensor is insensitive to axial shaft movements (the actual allowable axial shaft movement depends on the physical “length” of the magnetically encoded region).
- 20 ☐ Magnetically encoded SH remains neutral and has little to non magnetic field when no forces (like torque) are applied to the SH.
- ☐ Sensitive to mechanical forces in all three dimensional axis.

25

In the following, the Magnetic Flux Distribution in the SH will be described.

The PCME processing technology is based on using electrical currents, passing through the SH (Sensor Host or Shaft) to achieve the desired, permanent magnetic encoding of the Ferro-magnetic material. To achieve the desired sensor performance and features a very specific and well controlled electrical current is required. Early  
5 experiments that used DC currents failed because of lack of understanding how small amounts and large amounts of DC electric current are travelling through a conductor (in this case the “conductor” is the mechanical power transmitting shaft, also called Sensor Host or in short “SH”).

10 Referring to **Fig.17**, an assumed electrical current density in a conductor is illustrated.

It is widely assumed that the electric current density in a conductor is evenly distributed over the entire cross-section of the conductor when an electric current  
15 (DC) passes through the conductor.

Referring to **Fig.18**, a small electrical current forming magnetic field that ties current path in a conductor is shown.

20 It is our experience that when a small amount of electrical current (DC) is passing through the conductor that the current density is highest at the centre of the conductor. The two main reasons for this are: The electric current passing through a conductor generates a magnetic field that is tying together the current path in the centre of the conductor, and the impedance is the lowest in the centre of the  
25 conductor.

Referring to **Fig.19**, a typical flow of small electrical currents in a conductor is illustrated.

In reality, however, the electric current may not flow in a “straight” line from one connection pole to the other (similar to the shape of electric lightening in the sky).

- 5 At a certain level of electric current the generated magnetic field is large enough to cause a permanent magnetization of the Ferro-magnetic shaft material. As the electric current is flowing near or at the centre of the SH, the permanently stored magnetic field will reside at the same location: near or at the centre of the SH. When now applying mechanical torque or linear force for oscillation/reciprocation to the
- 10 shaft, then shaft internally stored magnetic field will respond by tilting its magnetic flux path in accordance to the applied mechanical force. As the permanently stored magnetic field lies deep below the shaft surface the measurable effects are very small, not uniform and therefore not sufficient to build a reliable NCT sensor system.
- 15 Referring to **Fig.20**, a uniform current density in a conductor at saturation level is shown.

- Only at the saturation level is the electric current density (when applying DC) evenly distributed at the entire cross section of the conductor. The amount of electrical
- 20 current to achieve this saturation level is extremely high and is mainly influenced by the cross section and conductivity (impedance) of the used conductor.

- Referring to **Fig.21**, electric current travelling beneath or at the surface of the conductor (Skin-Effect) is shown.

- 25 It is also widely assumed that when passing through alternating current (like a radio frequency signal) through a conductor that the signal is passing through the skin layers of the conductor, called the Skin Effect. The chosen frequency of the

- alternating current defines the “Location / position” and “depth” of the Skin Effect. At high frequencies the electrical current will travel right at or near the surface of the conductor (A) while at lower frequencies (in the 5 to 10 Hz regions for a 20 mm diameter SH) the electrical alternating current will penetrate more the centre of the shafts cross section (E). Also, the relative current density is higher in the current occupied regions at higher AC frequencies in comparison to the relative current density near the centre of the shaft at very low AC frequencies (as there is more space available for the current to flow through).
- 5
- 10 Referring to **Fig.22**, the electrical current density of an electrical conductor (cross-section 90 deg to the current flow) when passing through the conductor an alternating current at different frequencies is illustrated.

- The desired magnetic field design of the PCME sensor technology are two circular magnetic field structures, stored in two layers on top of each other (“Picky-Back”), and running in opposite direction to each other (Counter-Circular).
- 15

- Again referring to **Fig.13**, a desired magnetic sensor structure is shown: two endless magnetic loops placed on top of each other, running in opposite directions to each other: Counter-Circular “Picky-Back” Field Design.
- 20

- To make this magnetic field design highly sensitive to mechanical stresses that will be applied to the SH (shaft), and to generate the largest sensor signal possible, the desired magnetic field structure has to be placed nearest to the shaft surface. Placing the circular magnetic fields to close to the centre of the SH will cause damping of the user available sensor-output-signal slope (most of the sensor signal will travel through the Ferro-magnetic shaft material as it has a much higher permeability in comparison to air), and increases the non-uniformity of the sensor signal (in relation
- 25

to shaft rotation and to axial movements of the shaft in relation to the secondary sensor.

Referring to **Fig.23**, magnetic field structures stored near the shaft surface and stored  
5 near the centre of the shaft are illustrated.

It may be difficult to achieve the desired permanent magnetic encoding of the SH when using AC (alternating current) as the polarity of the created magnetic field is constantly changing and therefore may act more as a Degaussing system.

10

The PCME technology requires that a strong electrical current (“uni-polar” or DC, to prevent erasing of the desired magnetic field structure) is travelling right below the shaft surface (to ensure that the sensor signal will be uniform and measurable at the outside of the shaft). In addition a Counter-Circular, “picky back” magnetic field  
15 structure needs to be formed.

20

It is possible to place the two Counter-Circular magnetic field structures in the shaft by storing them into the shaft one after each other. First the inner layer will be stored in the SH, and then the outer layer by using a weaker magnetic force (preventing that the inner layer will be neutralized and deleted by accident. To achieve this, the known “permanent” magnet encoding techniques can be applied as described in patents from FAST technology, or by using a combination of electrical current encoding and the “permanent” magnet encoding.

25

A much simpler and faster encoding process uses “only” electric current to achieve the desired Counter-Circular “Picky-Back” magnetic field structure. The most challenging part here is to generate the Counter-Circular magnetic field.

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A uniform electrical current will produce a uniform magnetic field, running around the electrical conductor in a 90 deg angle, in relation to the current direction (A).

When placing two conductors side-by-side (B) then the magnetic field between the two conductors seems to cancel-out the effect of each other (C). Although still

5 present, there is no detectable (or measurable) magnetic field between the closely placed two conductors. When placing a number of electrical conductors side-by-side (D) the “measurable” magnetic field seems to go around the outside the surface of the “flat” shaped conductor.

10 Referring to **Fig.24**, the magnetic effects when looking at the cross-section of a conductor with a uniform current flowing through them are shown.

The “flat” or rectangle shaped conductor has now been bent into a “U”-shape. When passing an electrical current through the “U”-shaped conductor then the magnetic

15 field following the outer dimensions of the “U”-shape is cancelling out the measurable effects in the inner halve of the “U”.

Referring to **Fig.25**, the zone inside the “U”-shaped conductor seem to be magnetically “Neutral” when an electrical current is flowing through the conductor.

20

When no mechanical stress is applied to the cross-section of a “U”-shaped conductor it seems that there is no magnetic field present inside of the “U” (F). But when bending or twisting the “U”-shaped conductor the magnetic field will no longer follow its original path (90 deg angle to the current flow). Depending on the applied

25 mechanical forces, the magnetic field begins to change slightly its path. At that time the magnetic-field-vector that is caused by the mechanical stress can be sensed and measured at the surface of the conductor, inside and outside of the “U”-shape. Note: This phenomena is applies only at very specific electrical current levels.

The same applies to the “O”-shaped conductor design. When passing a uniform electrical current through an “O”-shaped conductor (Tube) the measurable magnetic effects inside of the “O” (Tube) have cancelled-out each other (G).

5

Referring to **Fig.26**, the zone inside the “O”-shaped conductor seem to be magnetically “Neutral” when an electrical current is flowing through the conductor.

10 However, when mechanical stresses are applied to the “O”-shaped conductor (Tube) it becomes evident that there has been a magnetic field present at the inner side of the “O”-shaped conductor. The inner, counter directional magnetic field (as well as the outer magnetic field) begins to tilt in relation to the applied torque stresses. This tilting field can be clearly sensed and measured.

15 In the following, an Encoding Pulse Design will be described.

To achieve the desired magnetic field structure (Counter-Circular, Picky-Back, Fields Design) inside the SH, according to an exemplary embodiment of a method of the present invention, unipolar electrical current pulses are passed through the Shaft  
20 (or SH). By using “pulses” the desired “Skin-Effect” can be achieved. By using a “unipolar” current direction (not changing the direction of the electrical current) the generated magnetic effect will not be erased accidentally.

The used current pulse shape is most critical to achieve the desired PCME sensor  
25 design. Each parameter has to be accurately and repeatable controlled: Current raising time, Constant current on-time, Maximal current amplitude, and Current falling time. In addition it is very critical that the current enters and exits very uniformly around the entire shaft surface.



In the following, a Rectangle Current Pulse Shape will be described.

Referring to **Fig.27**, a rectangle shaped electrical current pulse is illustrated.

5

A rectangle shaped current pulse has a fast raising positive edge and a fast falling current edge. When passing a rectangle shaped current pulse through the SH, the raising edge is responsible for forming the targeted magnetic structure of the PCME sensor while the flat “on” time and the falling edge of the rectangle shaped current pulse are counter productive.

10

Referring to **Fig.28**, a relationship between rectangles shaped Current Encoding Pulse-Width (Constant Current On-Time) and Sensor Output Signal Slope is shown.

15 In the following example a rectangle shaped current pulse has been used to generate and store the Coueter-Circilar “Picky-Back” field in a 15 mm diameter, 14CrNi14 shaft. The pulsed electric current had its maximum at around 270 Ampere. The pulse “on-time” has been electronically controlled. Because of the high frequency component in the rising and falling edge of the encoding pulse, this experiment can not truly represent the effects of a true DC encoding SH. Therefore the Sensor-  
20 Output-Signal Slope-curve eventually flattens-out at above 20 mV/Nm when passing the Constant-Current On-Time of 1000 ms.

Without using a fast raising current-pulse edge (like using a controlled ramping  
25 slope) the sensor output signal slope would have been very poor (below 10 mV/Nm). Note: In this experiment (using 14CrNi14) the signal hysteresis was around 0.95% of the FS signal (FS = 75 Nm torque).

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Referring to **Fig.29**, increasing the Sensor-Output Signal-Slope by using several rectangle shaped current pulses in succession is shown.

5 The Sensor-Output-Signal slope can be improved when using several rectangle shaped current-encoding-pulses in successions. In comparisons to other encoding-pulse-shapes the fast falling current-pulse signal slope of the rectangle shaped current pulse will prevent that the Sensor-Output-Signal slope may ever reach an optimal performance level. Meaning that after only a few current pulses (2 to 10) have been applied to the SH (or Shaft) the Sensor-Output Signal-Slope will no longer rise.

10

In the following, a Discharge Current Pulse Shape is described.

15 The Discharge-Current-Pulse has no Constant-Current ON-Time and has no fast falling edge. Therefore the primary and most felt effect in the magnetic encoding of the SH is the fast raising edge of this current pulse type.

As shown in **Fig.30**, a sharp raising current edge and a typical discharging curve provides best results when creating a PCME sensor.

20 Referring to **Fig.31**, a PCME Sensor-Output Signal-Slope optimization by identifying the right pulse current is illustrated.

25 At the very low end of the pulse current scale (0 to 75 A for a 15 mm diameter shaft, 14CrNi14 shaft material) the "Discharge-Current-Pulse type is not powerful enough to cross the magnetic threshold needed to create a lasting magnetic field inside the Ferro magnetic shaft. When increasing the pulse current amplitude the double circular magnetic field structure begins to form below the shaft surface. As the pulse current amplitude increases so does the achievable torque sensor-output signal-

amplitude of the secondary sensor system. At around 400A to 425A the optimal PCME sensor design has been achieved (the two counter flowing magnetic regions have reached their most optimal distance to each other and the correct flux density for best sensor performances.

5

Referring to **Fig.32**, Sensor Host (SH) cross section with the optimal PCME electrical current density and location during the encoding pulse is illustrated.

When increasing further the pulse current amplitude the absolute, torque force related, sensor signal amplitude will further increase (curve 2) for some time while the overall PCME-typical sensor performances will decrease (curve 1). When passing 900A Pulse Current Amplitude (for a 15 mm diameter shaft) the absolute, torque force related, sensor signal amplitude will begin to drop as well (curve 2) while the PCME sensor performances are now very poor (curve 1).

15

Referring to **Fig.33**, Sensor Host (SH) cross sections and the electrical pulse current density at different and increasing pulse current levels is shown.

As the electrical current occupies a larger cross section in the SH the spacing between the inner circular region and the outer (near the shaft surface) circular region becomes larger.

20

Referring to **Fig.34**, better PCME sensor performances will be achieved when the spacing between the Counter-Circular "Picky-Back" Field design is narrow (A).

25

The desired double, counter flow, circular magnetic field structure will be less able to create a close loop structure under torque forces which results in a decreasing secondary sensor signal amplitude.

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Referring to **Fig.35**, flattening-out the current-discharge curve will also increase the Sensor-Output Signal-Slope.

- 5     When increasing the Current-Pulse discharge time (making the current pulse wider)  
(B) the Sensor-Output Signal-Slope will increase. However the required amount of  
current is very high to reduce the slope of the falling edge of the current pulse. It  
might be more practical to use a combination of a high current amplitude (with the  
optimal value) and the slowest possible discharge time to achieve the highest  
10    possible Sensor-Output Signal Slope.

In the following, Electrical Connection Devices in the frame of Primary Sensor  
Processing will be described.

- 15    The PCME technology (it has to be noted that the term 'PCME' technology is used  
to refer to exemplary embodiments of the present invention) relies on passing  
through the shaft very high amounts of pulse-modulated electrical current at the  
location where the Primary Sensor should be produced. When the surface of the shaft  
is very clean and highly conductive a multi-point Copper or Gold connection may be  
20    sufficient to achieve the desired sensor signal uniformity. Important is that the  
Impedance is identical of each connection point to the shaft surface. This can be best  
achieved when assuring the cable length (L) is identical before it joins the main  
current connection point (I).
- 25    Referring to **Fig.36**, a simple electrical multi-point connection to the shaft surface is  
illustrated.

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However, in most cases a reliable and repeatable multi-point electrical connection can be only achieved by ensuring that the impedance at each connection point is identical and constant. Using a spring pushed, sharpened connector will penetrate possible oxidation or isolation layers (maybe caused by finger prints) at the shaft surface.

Referring to **Fig.37**, a multi channel, electrical connecting fixture, with spring loaded contact points is illustrated.

When processing the shaft it is most important that the electrical current is injected and extracted from the shaft in the most uniform way possible. The above drawing shows several electrical, from each other insulated, connectors that are held by a fixture around the shaft. This device is called a Shaft-Processing-Holding-Clamp (or SPHC). The number of electrical connectors required in a SPHC depends on the shafts outer diameter. The larger the outer diameter, the more connectors are required. The spacing between the electrical conductors has to be identical from one connecting point to the next connecting point. This method is called Symmetrical-“Spot”-Contacts.

Referring to **Fig.38**, it is illustrated that increasing the number of electrical connection points will assist the efforts of entering and exiting the Pulse-Modulated electrical current. It will also increase the complexity of the required electronic control system.

Referring to **Fig.39**, an example of how to open the SPHC for easy shaft loading is shown.

In the following, an encoding scheme in the frame of Primary Sensor Processing will be described.

- 5 The encoding of the primary shaft can be done by using permanent magnets applied at a rotating shaft or using electric currents passing through the desired section of the shaft. When using permanent magnets a very complex, sequential procedure is necessary to put the two layers of closed loop magnetic fields, on top of each other, in the shaft. When using the PCME procedure the electric current has to enter the  
10 shaft and exit the shaft in the most symmetrical way possible to achieve the desired performances.

- Referring to **Fig.40**, two SPHCs (Shaft Processing Holding Clamps) are placed at the borders of the planned sensing encoding region. Through one SPHC the pulsed  
15 electrical current (I) will enter the shaft, while at the second SPHC the pulsed electrical current (I) will exit the shaft. The region between the two SPHCs will then turn into the primary sensor.

- This particular sensor process will produce a Single Field (SF) encoded region. One  
20 benefit of this design (in comparison to those that are described below) is that this design is insensitive to any axial shaft movements in relation to the location of the secondary sensor devices. The disadvantage of this design is that when using axial (or in-line) placed MFS coils the system will be sensitive to magnetic stray fields (like the earth magnetic field).

- 25 Referring to **Fig.41**, a Dual Field (DF) encoded region (meaning two independent functioning sensor regions with opposite polarity, side-by-side) allows cancelling the effects of uniform magnetic stray fields when using axial (or in-line) placed MFS

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coils. However, this primary sensor design also shortens the tolerable range of shaft movement in axial direction (in relation to the location of the MFS coils). There are two ways to produce a Dual Field (DF) encoded region with the PCME technology. The sequential process, where the magnetic encoded sections are produced one after  
5 each other, and the parallel process, where both magnetic encoded sections are produced at the same time.

The first process step of the sequential dual field design is to magnetically encode one sensor section (identically to the Single Field procedure), whereby the spacing  
10 between the two SPHC has to be halve of the desired final length of the Primary Sensor region. To simplify the explanations of this process we call the SPHC that is placed in the centre of the final Primary Sensor Region the Centre SPHC (C-SPHC), and the SPHC that is located at the left side of the Centre SPHC: L-SPHC.

15 Referring to **Fig.42**, the second process step of the sequential Dual Field encoding will use the SPHC that is located in the centre of the Primary Sensor region (called C-SPHC) and a second SPHC that is placed at the other side (the right side) of the centre SPHC, called R-SPHC. Important is that the current flow direction in the centre SPHC (C-SPHC) is identical at both process steps.

20 Referring to **Fig.43**, the performance of the final Primary Sensor Region depends on how close the two encoded regions can be placed in relation to each other. And this is dependent on the design of the used centre SPHC. The narrower the in-line space contact dimensions are of the C-SPHC, the better are the performances of the Dual  
25 Field PCME sensor.

**Fig.44** shows the pulse application according to another exemplary embodiment of the present invention. As may be taken from the above drawing, the pulse is applied to

three locations of the shaft. Due to the current distribution to both sides of the middle electrode where the current  $I$  is entered into the shaft, the current leaving the shaft at the lateral electrodes is only half the current entered at the middle electrode, namely  $\frac{1}{2} I$ . The electrodes are depicted as rings which dimensions are adapted to the  
5 dimensions of the outer surface of the shaft. However, it has to be noted that other electrodes may be used, such as the electrodes comprising a plurality of pin electrodes described later in this text.

Referring to **Fig.45**, magnetic flux directions of the two sensor sections of a Dual  
10 Field PCME sensor design are shown when no torque or linear motion stress is applied to the shaft. The counter flow magnetic flux loops do not interact with each other.

Referring to **Fig.46**, when torque forces or linear stress forces are applied in a  
15 particular direction then the magnetic flux loops begin to run with an increasing tilting angle inside the shaft. When the tilted magnetic flux reaches the PCME segment boundary then the flux line interacts with the counterflowing magnetic flux lines, as shown.

Referring to **Fig.47**, when the applied torque direction is changing (for example from  
20 clock-wise to counter-clock-wise) so will change the tilting angle of the counterflow magnetic flux structures inside the PCM Encoded shaft.

In the following, a Multi Channel Current Driver for Shaft Processing will be  
25 described.

In cases where an absolute identical impedance of the current path to the shaft surface can not be guaranteed, then electric current controlled driver stages can be used to overcome this problem.



Referring to **Fig.48**, a six-channel synchronized Pulse current driver system for small diameter Sensor Hosts (SH) is shown. As the shaft diameter increases so will the number of current driver channels.

5

In the following, Bras Ring Contacts and Symmetrical “Spot” Contacts will be described.

When the shaft diameter is relative small and the shaft surface is clean and free from any oxidations at the desired Sensing Region, then a simple “Bras”-ring (or Copper-ring) contact method can be chosen to process the Primary Sensor.

10

Referring to **Fig.49**, bras-rings (or Copper-rings) tightly fitted to the shaft surface may be used, with solder connections for the electrical wires. The area between the two Bras-rings (Copper-rings) is the encoded region.

15

However, it is very likely that the achievable RSU performances are much lower then when using the Symmetrical “Spot” Contact method.

20 In the following, a Hot-Spotting concept will be described.

A standard single field (SF) PCME sensor has very poor Hot-Spotting performances. The external magnetic flux profile of the SF PCME sensor segment (when torque is applied) is very sensitive to possible changes (in relation to Ferro magnetic material) in the nearby environment. As the magnetic boundaries of the SF encoded sensor segment are not well defined (not “Pinned Down”) they can “extend” towards the direction where Ferro magnet material is placed near the PCME sensing region.

25

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Referring to **Fig.50**, a PCME process magnetized sensing region is very sensitive to Ferro magnetic materials that may come close to the boundaries of the sensing regions.

- 5 To reduce the Hot-Spotting sensor sensitivity the PCME sensor segment boundaries have to be better defined by pinning them down (they can no longer move).

Referring to **Fig.51**, a PCME processed Sensing region with two “Pinning Field Regions” is shown, one on each side of the Sensing Region.

10

By placing Pinning Regions closely on either side the Sensing Region, the Sensing Region Boundary has been pinned down to a very specific location. When Ferro magnetic material is coming close to the Sensing Region, it may have an effect on the outer boundaries of the Pinning Regions, but it will have very limited effects on the Sensing Region Boundaries.

15

There are a number of different ways, according to exemplary embodiments of the present invention how the SH (Sensor Host) can be processed to get a Single Field (SF) Sensing Region and two Pinning Regions, one on each side of the Sensing Region. Either each region is processed after each other (Sequential Processing) or two or three regions are processed simultaneously (Parallel Processing). The Parallel Processing provides a more uniform sensor (reduced parasitic fields) but requires much higher levels of electrical current to get to the targeted sensor signal slope.

20

- 25 Referring to **Fig.52**, a parallel processing example for a Single Field (SF) PCME sensor with Pinning Regions on either side of the main sensing region is illustrated, in order to reduce (or even eliminate) Hot-Spotting.

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A Dual Field PCME Sensor is less sensitive to the effects of Hot-Spotting as the sensor centre region is already Pinned-Down. However, the remaining Hot-Spotting sensitivity can be further reduced by placing Pinning Regions on either side of the Dual-Field Sensor Region.

5

Referring to **Fig.53**, a Dual Field (DF) PCME sensor with Pinning Regions either side is shown.

When Pinning Regions are not allowed or possible (example: limited axial spacing  
10 available) then the Sensing Region has to be magnetically shielded from the influences of external Ferro Magnetic Materials.

In the following, the Rotational Signal Uniformity (RSU) will be explained.

15 The RSU sensor performance are, according to current understanding, mainly depending on how circumferentially uniform the electrical current entered and exited the SH surface, and the physical space between the electrical current entry and exit points. The larger the spacing between the current entry and exit points, the better is the RSU performance.

20

Referring to **Fig.54**, when the spacings between the individual circumferentially placed current entry points are relatively large in relation to the shaft diameter (and equally large are the spacings between the circumferentially placed current exit points) then this will result in very poor RSU performances. In such a case the length of the PCM

25 Encoding Segment has to be as large as possible as otherwise the created magnetic field will be circumferentially non-uniform.

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Referring to **Fig.55**, by widening the PCM Encoding Segment the circumferentially magnetic field distribution will become more uniform (and eventually almost perfect) at the halve distance between the current entry and current exit points. Therefore the RSU performance of the PCME sensor is best at the halve way-point  
5 between of the current-entry / current-exit points.

Next, the basic design issues of a NCT sensor system will be described.

Without going into the specific details of the PCM-Encoding technology, the end-  
10 user of this sensing technology need to now some design details that will allow him to apply and to use this sensing concept in his application. The following pages describe the basic elements of a magnetostriction based NCT sensor (like the primary sensor, secondary sensor, and the SCSP electronics), what the individual components look like, and what choices need to be made when integrating this technology into an  
15 already existing product.

In principle the PCME sensing technology can be used to produce a stand-alone sensor product. However, in already existing industrial applications there is little to none space available for a “stand-alone” product. The PCME technology can be  
20 applied in an existing product without the need of redesigning the final product.

In case a stand-alone torque sensor device or position detecting sensor device will be applied to a motor-transmission system it may require that the entire system need to undergo a major design change.  
25

In the following, referring to Fig.56, a possible location of a PCME sensor at the shaft of an engine is illustrated.

Fig. 56 shows possible arrangement locations for the torque sensor according to an exemplary embodiment of the present invention, for example, in a gear box of a motorcar. The upper portion of Fig. 56 shows the arrangement of the PCME torque sensor according to an exemplary embodiment of the present invention. The lower  
5 portion of the Fig. 56 shows the arrangement of a stand alone sensor device which is not integrated in the input shaft of the gear box as is in the exemplary embodiment of the present invention.

As may be taken from the upper portion of Fig. 56, the torque sensor according to an  
10 exemplary embodiment of the present invention may be integrated into the input shaft of the gear box. In other words, the primary sensor may be a portion of the input shaft. In other words, the input shaft may be magnetically encoded such that it becomes the primary sensor or sensor element itself. The secondary sensors, i.e. the  
15 coils, may, for example, be accommodated in a bearing portion close to the encoded region of the input shaft. Due to this, for providing the torque sensor between the power source and the gear box, it is not necessary to interrupt the input shaft and to provide a separate torque sensor in between a shaft going to the motor and another shaft going to the gear box as shown in the lower portion of Fig. 56.

20 Due to the integration of the encoded region in the input shaft it is possible to provide for a torque sensor without making any alterations to the input shaft, for example, for a car. This becomes very important, for example, in parts for an aircraft where each part has to undergo extensive tests before being allowed for use in the aircraft. Such torque sensor according to the present invention may be perhaps even  
25 without such extensive testing being incorporated in shafts in aircraft or turbine since, the immediate shaft is not altered. Also, no material effects are caused to the material of the shaft.

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Furthermore, as may be taken from Fig. 56, the torque sensor according to an exemplary embodiment of the present invention may allow to reduce a distance between a gear box and a power source since the provision of a separate stand alone torque sensor between the shaft exiting the power source and the input shaft to the gear box becomes obvious.

Next, Sensor Components will be explained.

A non-contact magnetostriction sensor (NCT-Sensor), as shown in **Fig.57**, may consist, according to an exemplary embodiment of the present invention, of three main functional elements: The Primary Sensor, the Secondary Sensor, and the Signal Conditioning & Signal Processing (SCSP) electronics.

Depending on the application type (volume and quality demands, targeted manufacturing cost, manufacturing process flow) the customer can chose to purchase either the individual components to build the sensor system under his own management, or can subcontract the production of the individual modules.

**Fig.58** shows a schematic illustration of components of a non-contact torque sensing device. However, these components can also be implemented in a non-contact position sensing device.

In cases where the annual production target is in the thousands of units it may be more efficient to integrate the “primary-sensor magnetic-encoding-process” into the customers manufacturing process. In such a case the customer needs to purchase application specific “magnetic encoding equipment”.

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In high volume applications, where cost and the integrity of the manufacturing process are critical, it is typical that NCTE supplies only the individual basic components and equipment necessary to build a non-contact sensor:

- 5        ☐ ICs (surface mount packaged, Application-Specific Electronic Circuits)
  - ☐ MFS-Coils (as part of the Secondary Sensor)
  - ☐ Sensor Host Encoding Equipment (to apply the magnetic encoding on the shaft = Primary Sensor)
- 10    Depending on the required volume, the MFS-Coils can be supplied already assembled on a frame, and if desired, electrically attached to a wire harness with connector. Equally the SCSP (Signal Conditioning & Signal Processing) electronics can be supplied fully functional in PCB format, with or without the MFS-Coils embedded in the PCB.

15

**Fig.59** shows components of a sensing device.

- As can be seen from **Fig.60**, the number of required MFS-coils is dependent on the expected sensor performance and the mechanical tolerances of the physical sensor design. In a well designed sensor system with perfect Sensor Host (SH or magnetically encoded shaft) and minimal interferences from unwanted magnetic stray fields, only 2 MFS-coils are needed. However, if the SH is moving radial or axial in relation to the secondary sensor position by more than a few tenths of a millimeter, then the number of MFS-coils need to be increased to achieve the desired sensor performance.
- 20
- 25

In the following, a control and/or evaluation circuitry will be explained.

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The SCSP electronics, according to an exemplary embodiment of the present invention, consist of the NCTE specific ICs, a number of external passive and active electronic circuits, the printed circuit board (PCB), and the SCSP housing or casing. Depending on the environment where the SCSP unit will be used the casing has to be sealed appropriately.

Depending on the application specific requirements NCTE (according to an exemplary embodiment of the present invention) offers a number of different application specific circuits:

10

- ☐ Basic Circuit
- ☐ Basic Circuit with integrated Voltage Regulator
- ☐ High Signal Bandwidth Circuit
- ☐ Optional High Voltage and Short Circuit Protection Device
- 15 ☐ Optional Fault Detection Circuit

**Fig.61** shows a single channel, low cost sensor electronics solution.

As may be taken from Fig. 61, there may be provided a secondary sensor unit which comprises, for example, coils. These coils are arranged as, for example, shown in Fig. 60 for sensing variations in a magnetic field emitted from the primary sensor unit, i.e. the sensor shaft or sensor element when torque is applied thereto. The secondary sensor unit is connected to a basis IC in a SCST. The basic IC is connected via a voltage regulator to a positive supply voltage. The basic IC is also connected to ground. The basic IC is adapted to provide an analog output to the outside of the SCST which output corresponds to the variation of the magnetic field caused by the stress applied to the sensor element.



**Fig.62** shows a dual channel, short circuit protected system design with integrated fault detection. This design consists of 5 ASIC devices and provides a high degree of system safety. The Fault-Detection IC identifies when there is a wire breakage anywhere in the sensor system, a fault with the MFS coils, or a fault in the electronic driver stages of the “Basic IC”.

Next, the Secondary Sensor Unit will be explained.

The Secondary Sensor may, according to one embodiment shown in **Fig.63**, consist of the elements: One to eight MFS (Magnetic Field Sensor) Coils, the Alignment- & Connection-Plate, the wire harness with connector, and the Secondary-Sensor-Housing.

The MFS-coils may be mounted onto the Alignment-Plate. Usually the Alignment-Plate allows that the two connection wires of each MFS-Coil are soldered / connected in the appropriate way. The wire harness is connected to the alignment plate. This, completely assembled with the MFS-Coils and wire harness, is then embedded or held by the Secondary-Sensor-Housing.

The main element of the MFS-Coil is the core wire, which has to be made out of an amorphous-like material.

Depending on the environment where the Secondary-Sensor-Unit will be used, the assembled Alignment Plate has to be covered by protective material. This material can not cause mechanical stress or pressure on the MFS-coils when the ambient temperature is changing.

In applications where the operating temperature will not exceed +110 deg C the customer has the option to place the SCSP electronics (ASIC) inside the secondary sensor unit (SSU). While the ASIC devices can operated at temperatures above +125 deg C it will become increasingly more difficult to compensate the temperature  
5 related signal-offset and signal-gain changes.

The recommended maximal cable length between the MFS-coils and the SCSP electronics is 2 meters. When using the appropriate connecting cable, distances of up to 10 meters are achievable. To avoid signal-cross-talk in multi-channel applications  
10 (two independent SSUs operating at the same Primary Sensor location = Redundant Sensor Function), specially shielded cable between the SSUs and the SCSP Electronics should be considered.

When planning to produce the Secondary-Sensor-Unit (SSU) the producer has to  
15 decide which part / parts of the SSU have to be purchased through subcontracting and which manufacturing steps will be made in-house.

In the following, Secondary Sensor Unit Manufacturing Options will be described.

20 When integrating the NCT-Sensor into a customized tool or standard transmission system then the systems manufacturer has several options to choose from:

- ☐ custom made SSU (including the wire harness and connector)
- ☐ selected modules or components; the final SSU assembly and system test may  
25 be done under the customer's management.
- ☐ only the essential components (MFS-coils or MFS-core-wire, Application specific ICs) and will produce the SSU in-house.

**Fig.64** illustrates an exemplary embodiment of a Secondary Sensor Unit Assembly.

Next, a Primary Sensor Design is explained.

- 5     The SSU (Secondary Sensor Units) can be placed outside the magnetically encoded SH (Sensor Host) or, in case the SH is hollow, inside the SH. The achievable sensor signal amplitude is of equal strength but has a much better signal-to-noise performance when placed inside the hollow shaft.
- 10    **Fig.65** illustrates two configurations of the geometrical arrangement of Primary Sensor and Secondary Sensor.

- Improved sensor performances may be achieved when the magnetic encoding process is applied to a straight and parallel section of the SH (shaft). For a shaft with
- 15    15 mm to 25 mm diameter the optimal minimum length of the Magnetically Encoded Region is 25 mm. The sensor performances will further improve if the region can be made as long as 45 mm (adding Guard Regions). In complex and highly integrated transmission (gearbox) systems it will be difficult to find such space. Under more ideal circumstances, the Magnetically Encoding Region can be as short as 14 mm,
- 20    but this bears the risk that not all of the desired sensor performances can be achieved.

- As illustrated in **Fig.66**, the spacing between the SSU (Secondary Sensor Unit) and the Sensor Host surface, according to an exemplary embodiment of the present invention, should be held as small as possible to achieve the best possible signal quality.

25

Next, the Primary Sensor Encoding Equipment will be described.

An example is shown in **Fig.67**.

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Depending on which magnetostriction sensing technology will be chosen, the Sensor Host (SH) needs to be processed and treated accordingly. The technologies vary by a great deal from each other (ABB, FAST, FT, Kubota, MDI, NCTE, RM, Siemens, ... ) and so does the processing equipment required. Some of the available magnetostriction sensing technologies do not need any physical changes to be made on the SH and rely only on magnetic processing (MDI, FAST, NCTE).

While the MDI technology is a two phase process, the FAST technology is a three phase process, and the NCTE technology a one phase process, called PCM Encoding.

One should be aware that after the magnetic processing, the Sensor Host (SH or Shaft), has become a “precision measurement” device and has to be treated accordingly. The magnetic processing should be the very last step before the treated SH is carefully placed in its final location.

The magnetic processing should be an integral part of the customer’s production process (in-house magnetic processing) under the following circumstances:

- ☐ High production quantities (like in the thousands)
- ☐ Heavy or difficult to handle SH (e.g. high shipping costs)
- ☐ Very specific quality and inspection demands (e.g. defense applications)

In all other cases it may be more cost effective to get the SH magnetically treated by a qualified and authorized subcontractor, such as NCTE. For the “in-house” magnetic processing dedicated manufacturing equipment is required. Such equipment can be operated fully manually, semi-automated, and fully automated. Depending on the

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complexity and automation level the equipment can cost anywhere from EUR 20k to above EUR 500k.

5 **Fig. 68A** shows a magnetizing apparatus 140 for magnetizing a shaft 150 to form a magnetically encoded region on the shaft 150. The magnetizing apparatus 140 does not involve a shaft which is enclosed by another object. When a current signal is applied between different ends of the shaft 150, the shaft 150 is magnetized.

10 **Fig. 68B** shows a magnetizing apparatus 160 according to the invention involving a hollow tube 121 enclosing a shaft 150 (not shown in Fig. 68B) to be magnetized. An end portion of the shaft 150 is coupled with an end portion of the hollow tube 121 enclosing the shaft 150. When a current signal is applied to the shaft 150, the current is injected in the hollow tube 121. The magnetic field generated by the current flowing in the hollow tube 121 stabilizes the current distribution in the shaft 150.  
15 Thus, the shaft 150 is magnetized in a very homogenous manner.

**Fig. 68C** shows a schematic view of a torque and force sensing device 170 with a magnetically encoded region 122 formed according to the magnetization generation process carried out with the magnetizing apparatus 160. The length of the  
20 magnetically encoded region 122 is defined by the length along which the current flows during the magnetization procedure (i.e. depends on the geometry of the contacts for injecting a magnetizing current).

Fig. 68C shows the torque sensor 170 having the shaft 150 which may rotate with a  
25 predetermined value of torque, wherein a portion of the shaft 150 is magnetized to form a magnetically encoded region 122. When the shaft 150 rotates, the magnetically encoded region 122 generates a magnetic signal in a magnetic field detecting coil 123.

5     **Fig. 68D** shows a signal versus torque diagram 100 (an experimentally measured curve and a schematic curve emphasizing the features of the measured curve) of a torque and force sensing device magnetized with the magnetizing apparatus 140 shown in Fig. 68A.

10     **Fig. 68E** shows a signal versus torque diagram 110 (an experimentally measured curve and a schematic curve emphasizing the features of the measured curve) of a torque and force sensing device 170 magnetized with the magnetizing apparatus 160 shown in Fig. 68B.

15     The diagrams 100, 110 of Fig. 68D and Fig. 68E each have an abscissa 101 along which a torque is shown which is applied to a shaft with a magnetically encoded region. Figs. 68D and 68E show along an ordinate 102 the signal as detected by coil 123 when a particular value of the torque as plotted along the abscissa 101 is applied.

20     Figs. 68D and 68E show a hysteresis loop 103 and a best fit line 104, for both cases. As can be seen, the slope of the best fit line 104 is larger in Fig. 68E than in Fig. 68D, and the hysteresis properties are suppressed in Fig. 68E even better than in Fig. 68D.

25     One of the big challenges of the magnetic field encoding process according to the invention is to achieve a uniform electrical current distribution around a “to be encoded” shaft 150, i.e. to have a properly magnetized region 122. Failing to do so will result in a poor rotational signal uniformity performance and in a poor signal linearity.

Fig. 68D shows the sensors torque signal when the shaft 150 has been processed according to Fig. 68A. The sensor characteristics as shown in Fig. 68D shows some non-linearity which has a negative impact on the sensor signal hysteresis performance.

5

Processing the shaft 150 to form the magnetically encoded region 122 with the method as shown in Figs. 68B, 69, 70, greatly improves the sensors signal linearity and has a positive impact on the sensors signal hysteresis, which will become much smaller (see Fig. 68E).

10

The magnetically encoded sensor corresponding to Fig. 68A has a slope of the best fit line 104 of 13.8 mV/Nm, and a hysteresis of 3.72%. In contrast to this, the torque sensor magnetized according to Fig. 68B has, as shown in Fig. 68E, a slope of 15.1 mV/Nm and a hysteresis with only 2.59%.

15

Thus, the signal-to-noise ratio is significantly improved when the magnetically encoded region 122 is generated according to the invention.

A basic principle of the method for magnetizing an object according to the invention, which can also be denoted as a self-adjusting process, is to generate a counter magnetic field during the actual magnetization process, whereby this counter magnetic field ensures that the electrical signal passes through the shaft 150 very uniformly through the "to be encoded" sensing region 122.

25 By passing back the electrical signal for magnetizing a part of the shaft 150 to form the magnetically encoded region 122 through the conductive tube 121 enclosing the shaft 150, the magnetic field that develops at the inner side of the tube 121 can work hand in hand with the magnetic field that is developing at the outside of the shaft

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150. The shaft 150 is placed at the centre, inside the tube 121, and is not allowed to contact the tube 121, except at desired locations.

**Fig. 69** shows a scheme which may be useful for a further understanding of the invention. Thus, the arrangement shown in Fig. 69 shows the solid shaft 150 and the hollow tube 121. An electrical current  $I$  is injected in the solid shaft 150 to form a magnetic field around the solid shaft 150, as shown in Fig. 69. When this current  $I$  flows through the hollow tube 121, a further magnetic field is also generated in the material of the hollow tube 121. Thus, Fig. 69 is a schematic view illustrating a principle of a method for magnetizing an object according to the invention.

**Figs. 70A** and **70B** are schematic views illustrating an apparatus for magnetizing an object according to the invention.

15 In order to magnetize the shaft 150, the hollow tube 121 is arranged to enclose the solid shaft 150. Further, an electrical signal  $I$  is applied to the solid shaft 150. As shown in a diagram 310 of Fig. 70D having a time abscissa 301 and having a current ordinate 302, the pulsed current signal 300 has a fast raising edge which is essentially vertical and has a slow falling edge.

20 As can be further seen in Fig. 70A, the solid shaft 150 is arranged at the centre of the hollow tube 121. The hollow tube 121 has first electrical connection 201 and has a second electrical connection 202, wherein the second electrical connection 202 of the hollow tube 121 is coupled to a first electrical connection 203 of the solid shaft 150.  
25 Further, the solid shaft has a second electrical connection 204. An electrical signal source (not shown) is connected such that the current signal  $I$  can be applied between the first connection 201 of the hollow tube 121 and the second connection 204 of the solid shaft 150.



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Fig. 70B shows another view of the configuration of Fig. 70A.

Because the magnetic flux direction at the inside of the hollow tube 121 (caused by  
5 the return electrical current flow direction) is the same rotational direction as the  
magnetic field that goes around the solid shaft 150 (because of the forward electrical  
current flow direction), the magnetic field density will distribute itself uniformly in  
the space between the tube 121 and the shaft 150. Consequently, the electrical  
current that flows in the solid shaft 150 and the tube 121 will be evenly distributed in  
10 both items.

The resulting solution is that the rotational signal uniformity performance of the  
sensor signal improves greatly (see Fig. 68E), and with this the signal non-linearity  
and signal hysteresis (will become smaller), and in addition the signal slope increases  
15 (more signal at an applied torque).

Particular at the electrical connections between the electrical supply cables and the  
“to be encoded” shaft 150 the results are very challenging. Even the slightest  
differences in impedance where the cable connects with the shaft (or tube surface)  
20 will cause that the electrical current will be not uniformly distributed around the shaft  
150 at this particular area.

As the current is flowing further in the shaft 150, the electrical current density will  
become more and more uniformly around the shaft 150. If it would be possible to  
25 ensure that the electrical current enters uniformly around the shaft 150 right where  
the electrical wires are connected, then the useful sensing area will become larger  
(moves nearer to the point where the wires connect with the shaft 150).

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The method of magnetizing the shaft according to the invention is exactly doing that: it forces the electrical current to flow most uniformly (in respect when monitoring the current flow density 360° around the shaft).

- 5     Thus, the invention has the benefits that it simplifies the way the electrical connections need to be made to the shaft 150. Further, the invention improves greatly several sensor performances. Moreover, the encoding equipment is simplified, and with this the manufacturing equipment costs are reduced.
- 10    **Fig. 70C** shows an alternative arrangement of an apparatus for magnetizing the shaft 150. In addition to the first and the second connections 201, 202, the hollow tube 121 further has a third electrical connection 351, and the solid shaft 150 has a third electrical connection 352. In the case of Fig. 70C, two different pulses I1 and I2 are applied to the array in the manner as shown in Fig. 70C. The first electrical signal I1
- 15    is applied between the first electrical connection 201 of the hollow tube 121 and the second electrical connection 204 of the solid shaft 150. A second electrical signal I2 is applied between the third electrical connection 351 of the hollow tube 121 and the third electrical connection 352 of the solid shaft 150.
- 20    Further, an electrically conductive coupling element 350 is provided to couple the second electrical connection 202 of the hollow tube 121 to the first electrical connection 203 of the solid shaft 150. The current distribution shown in Fig. 70C achieves a magnetic field distribution which yields a homogeneous current profile in elements 121, 150, thus achieving a sensor with a well-defined magnetization, i.e. a
- 25    well-defined magnetically encoded region 122.

**Figs. 71A, 71B** illustrate another embodiment of an apparatus for magnetizing a shaft 150 according to the invention,

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Fig. 71A shows a configuration in which the coupling between the connection 202 of the hollow tube 121 and the connection 203 of the conductive solid shaft 150 are realized by a conductive based plate 400 as a coupling element.

5

Fig. 71B shows the apparatus of Fig. 71A in a state in which a current is applied. The current flows through the shaft 150, through the plate 400 and from there – in opposite direction compared to the flowing direction in the shaft 150 – through the tube 121. As can be seen in Fig. 71B, the current is applied to the tube 121 via a plurality of electrical connection cables which are arranged circumferentially along the perimeter of the upper circular surface of the tube 121. Such an arrangement with - for instance six or eight - cables yields a very homogeneous current distribution.

As an alternative to the provision of a conductive plate 400 for coupling the tube 121 to the shaft 150, the tube 121 can remain uncoupled from the shaft 150 (i.e. the plate 400 can be omitted), and two oppositely oriented current signals can be flown through the shaft 150 and through the tube 121, wherein the current in the shaft 150 may serve to magnetize the shaft 150, and the current in the tube 121 may serve to provide a counter magnetic field to increase the homogeneity of magnetizing the shaft 150. Thus, two signals are applied simultaneously, one to the tube 121 and the other one to the shaft 150.

In the following, referring to **Fig. 72**, an apparatus 500 for magnetizing a magnetizable tube 501 according to another embodiment of the invention will be described.

25

The apparatus 500 comprises the magnetizable tube 501, namely a hollow cylinder, a wire 502 having a first part 502a, a second part 502b and a third part 502c, wherein a

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current can flow through the wire 502. An electrical power source 503 is provided which can inject an electrical current in the wire 502 in an operation state in which a switch 504 is closed. Thus, by closing the switch 504, a pulse current 505 can be injected in wire 502. However, alternatively to the pulse current 505, a pulse as  
5 shown in Fig. 70D, for instance, can also be injected in the wire 502. Although a pulse as the one shown in Fig. 70D is preferred, any other appropriate pulse shape like the one shown in Fig. 72 can be injected in the wire 502.

The magnetizable tube 501 is made of industrial steel and has a wall thickness of 4  
10 cm, a diameter of 88 cm and a length of several metres. The tube 501 to be magnetized is arranged in such a manner that the tube 501 encloses the first part 502a of the wire 502. The electrical power source 503 is adapted to apply a pulsed current 505 to the wire 502, wherein the pulsed current 505 is adapted such that the magnetizable tube 501 becomes magnetized. When such a current pulse 505 is  
15 applied to the first part 502a of the wire 502, a magnetic field is generated in the vicinity and around the first part 502a of the wire 502 which influences, similar like in the case of a transformer, the elementary magnets within the magnetizable tube 501. Consequently, the pulse 505 will cause the tube 501 to become magnetized.

20 As can be seen in Fig. 72, the first part 502a of the wire 502 is arranged at the centre of the hollow tube 501. In contrast to the configuration shown in Fig. 70A to 70D, the electrical power source 503 is connected to the wire 502, but is disconnected from the magnetizable tube 501. Further, a hollow shielding cylinder 506 is provided which is manufactured similarly to the magnetizable tube 501. As can be further  
25 seen, particularly the third part 502c of the wire 502 is free from an enclosure with the magnetizable tube 501, i.e. is not surrounded by the magnetizable tube 501. The shielding cylinder 506 is arranged and adapted to electromagnetically shield (i.e. decouple) the third part 502c of the wire 502 being free from an enclosure with the

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magnetizable tube 501 from the magnetizable tube 501. The shielding tube 506 made of magnetizable material is arranged between the magnetizable tube 501 and the third part 502c of the wire 502. Thus, the current pulse 505 flowing through all parts 502a, 502b, 502c of the wire 502 acts on the magnetizable tube 501 essentially only  
5 at the first part 502a which is enclosed by the magnetizable tube 501, whereas the current flowing in a counter direction compared to the first part 502a through the third part 502c is avoided to negatively influence, particularly to weaken, the magnetization generated in the magnetizable tube 501.

10 Also the second part 502b of the wire 502 can be shielded from the magnetizable tube 501 by a similar shielding element like the shielding cylinder 506.

**Fig. 73A** shows a schematic top view of the apparatus 500. As can be seen, the shielding cylinder 506 efficiently shields the third part 502c of the wire 502 from the  
15 tube 501.

**Figs. 73B to 73D** show further embodiments of shielding elements.

Fig. 73B shows a configuration in which four shielding cylinders 600 to 603 are  
20 arranged around the third part 502c of the wire 502. Thus, the shielding cylinders 600 to 603 made of magnetizable material are arranged surrounding the portion 502c of the wire 502 which is free from an enclosure with the magnetizable tube 501.

Fig. 73C shows a plurality of cylindrical shafts 610 to 617 which are arranged around  
25 the third part 502c of the wire 502 to shield the third part 502 being free of an enclosure with the magnetizable tube 501 from the magnetizable tube 501.

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Fig. 73D shows a six tubes 620 to 625 which are arranged to surround the third part 502c.

In the following, referring to **Fig. 74**, an apparatus 700 for magnetizing a  
5 magnetizable tube 501 according to another embodiment of the invention will be described.

According to the embodiment of Fig. 74, the shielding cylinder 506 is arranged to surround the third part 502c of the wire 502. Further, the electrical signal source 503  
10 is realized as a bank of (charged) capacitors 701 which may be discharged by closing the switch 504 to generate a pulse as the one shown in Fig. 71D. The magnetizing apparatus 700 is "mobile" which is illustrated by means of a vehicle 702 which transports the capacitor banks 701 to a place at which a magnetizable tube 501 (i.e. drilling equipment at a mining place) shall be magnetized.

15

Thus, the mobile processing unit of Fig. 74 can be brought closest to drilling or large tooling shafts.

In the following, referring to **Fig. 75A** and **Fig. 75B**, an apparatus 800 for calibrating  
20 a force and torque sensor device 810 will be described.

The apparatus 800 comprises the force and torque sensor device 810, a pre-known mass 811 with a weight of 1000 kg and a calibrating unit 818.

25 The force and torque sensor device 810 has a magnetically encoded region 812 on a hollow tube 813 and four magnetic field detecting coils 814 to 817.

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The pre-known weight 811 is put on the top of the force and torque sensor device 810 to apply a pre-known axial force to the magnetized hollow tube 813. The calibrating unit 818 which is connected to the magnetic field detecting coils 814 to 817 is adapted to calibrate the force and torque sensor 810 based on a correlation  
5 between the pre-known mass 811 and a detecting signal resulting from the pre-known force of the mass 811.

Thus, a pre-known mass 811 is applied on the top of the horizontally arranged hollow tube 813 which stands on a horizontal and stable base 819. As a consequence  
10 of the mass 811 applied to the top of the force and torque sensor device 810 (which may be magnetized in a manner as shown in Fig. 74), the magnetic field generated by the magnetically encoded region 812 changes so that a signal in the magnetic field detecting coils 814 to 817 occurs. Thus, this signal which is processed in the calibration unit 818 is correlated to the pre-known axial force applied to the  
15 magnetized tube 813 by the known mass 811. This pair of data pairs, namely the known axial force and the detected signal, can be stored in the calibration unit 818.

The upper surface of the hollow tube 813 (onto which the mass 811 is put) is for instance arranged horizontally so that the vector of the force generated by the mass  
20 811 on the top of the tube 813 is oriented essentially perpendicular to the surface of the hollow tube 813 (or is directed towards the center of the earth). In case that the upper surface of the tube 813 and/or the base 819 is/are not oriented in a horizontal manner, an angular correction calculation may be necessary or desirable.

25 When the drilling shaft 813 is brought back in the ground and is used for drilling, axial forces and torque applied to the drilling shaft 813 can be measured by the magnetic field detecting coils 814 to 817 and may be compared to the calibration

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signal. Thus, an absolute measurement of torque and force can be carried out based on a calibration with an axial load 811.

For the calibration, the coils 814 to 817 have to be arranged such that an axial force can be measured. For the torque sensing operation, the coils 814 to 817 have to be arranged such that torque can be measured. Thus, the axes of the coils 814 to 817 may have to be re-oriented, accordingly, when switching from a calibration mode to a measuring mode.

**Figs. 76A and 76B** show two possible configurations for arranging the magnetic field detecting coils 814 to 817.

**Fig. 77** shows three possible configurations of drilling shafts 1000 having magnetically encoded regions 1001, 1002 or 1003.

The markings 1001 to 1003 symbolize where the drilling shaft 1000 (or rotational power transmitting shaft 1000) have magnetically encoded regions. In real life, the encoding 1001 to 1003 is optically invisible and does not change or interfere with any of the mechanical properties of the shaft 1000. The drilling shaft 1000 can be encoded at a specific location 1001, or at a section 1002, or in its entirety 1003. In many cases, the encoding at a specific location 1001 is advisable for a static system operation only. The encoding options 1002, 1003 are particularly dedicated for applications where the drilling shaft 1000 is rotating or in motion in some ways.

**Fig. 78** shows two configurations how magnetic field detecting coils 1100 to 1103 may be arranged around the drilling shaft 1000.

In the following, referring to **Fig. 79**, an apparatus 6800 for magnetizing an object



will be explained.

As shown in Fig.79, the shaft 150 enclosed by the hollow tube 121 can be magnetized by applying an electrical signal generated by the electrical power source 503 to the hollow tube 121. The apparatus 6800 allows magnetizing the shaft 150 by arranging the hollow tube 121 in such a manner that the hollow tube 121 encloses the shaft 150, and by applying an electrical signal via a plurality of circumferentially arranged contacts to the hollow tube 121. The electrical signal generated by the electrical power source 503 is for instance a pulsed signal such that at least a portion of the shaft 150 is magnetized. As shown in Fig. 79, two end portions of the shaft 150 outside the hollow tube 121 are short-circuited by a wire 6801 located outside the hollow tube 121.

**Fig. 80** illustrates still another apparatus 6900 for magnetizing an object according to an embodiment of the invention.

The function of the apparatus 6900 is very similar to the function of the apparatus shown in Fig. 72A, Fig. 72B with the difference that the electrically conductive plate 400 is substituted by an electrically conductive fluid 6902 (e.g. mercury) which serves to electrically contact the shaft 150 to the hollow tube 121.

In the following, it is described how the apparatus 6900 is operated. A (for instance electrically insulating) spacer element 6901 in the form of a hollow cylinder with an inside diameter which essentially equals to the diameter of the shaft 150 and with an outside diameter which essentially equals to the inside diameter of the hollow tube 121 is arranged to seal and space the volume between the hollow tube 121 and the shaft 150 located within the hollow tube. Subsequently, the electrically conductive fluid 6902 is injected in the array 6900 to fill the space delimited by the hollow tube

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121 and the shaft 150 and the spacer element 6901 to electrically couple the hollow tube 121 and the shaft 150 in a very flexible manner.

In the following, referring to **Fig. 81**, an apparatus 7000 for calibrating a force and torque sensor device according to the invention will be explained.

The apparatus 7000 comprises a base 7001 for receiving a shaft 7002 of a torque sensing device. The torque sensing device further includes two magnetic field detection coils 7004 and a magnetically encoded region 7003 which may be formed, for instance, by the above-described PCME technology. The base 7001 receives the shaft 7002 in such a manner that the shaft cannot be moved or rotated by an applied force. A motor 7005 is adapted to drive a rotatable element 7006 (e.g. a flywheel) which in term can rotate in a controllable manner and which is coupled to the shaft 7002 such that a mechanical impulse of the rotatable element 7006 can be transferred to the shaft 7002 to apply a (reactive) torque to the shaft 7002. As a response to such a calibrating torque of a known value, a signal can be detected by the coils 7004 which can serve for a calibration of the torque sensing device. Thus, the apparatus 7000 has the driven rotatable element 7006 as a pre-known torque generating element. Particularly, a sudden change of the rotation state of the rotatable element 7006 (e.g. a sudden brake signal) is useful as a source of (reactive) torque applied as a calibrating signal to the torque sensing device.

It should be noted that the term “comprising” does not exclude other elements or steps and the “a” or “an” does not exclude a plurality. Also elements described in association with different embodiments may be combined.